## Remarks

The Office Action mailed September 11, 2008 has been received and reviewed. Claims 1-18, 20-75, and 78-88 are pending. Claims 10, 20, 56, 63, 75, 78, 79, and 80 are amended. Reconsideration and withdrawal of the rejections are respectfully requested.

## Claim Amendments

Claims 1, 10, 20, 32, 56, 63, 75, 78, 79, and 80 are amended to recite that the solubility parameter can be determined by measuring, obtaining the solubility parameter from a reference publication, taking an average of calculations performed using the Hoy Method and the Hoftyzer-van Krevelen Method, and calculating by computer simulation.

Support for the amendments may be found in Applicants' specification at, for example, from page 19, line 6 through page 25, including Table 1 at pages 20-25.

Claims 20, 63, 78, and 80 are amended to recite that the miscible polymer blend can include at least one hydrophobic cellulose derivative and at least one miscible polymer selected from the group consisting of polypropylene, polystyrene, poly(vinyl chloride), poly(vinyl bromide), poly(vinylidene chloride), poly(chloro trifluoroethylene), poly(vinyl alcohol), poly(vinyl acetate), poly(vinyl propionate), poly(methyl acylate), poly(ethyl acrylate), poly(propyl acrylate), poly(butyl acrylate), poly(isobutyl acrylate), poly(methyl methacrylate), poly(ethyl methacrylate), poly(butyl methacrylate), poly(isobutyl methacrylate), poly(tert-butyl methacrylate), poly(benzyl methacrylate), poly(ethoxyethyl methacrylate), polyacrylonitrile, polymethacrylonitrile, poly(alpha-cyanomethyl acrylate), polychloroprene, polyformaldehyde, poly(tetramethylene oxide), polyepichlorohydrin, poly(ethylene sulphide), poly(styrene sulphide), poly(ethylene terephthalate), poly(8-aminocaprylic acid), poly(hexamethylene adipamide), polyurethane hard segment (MDI + BDO), poly(bisphenyl A carbonate), cellulose acetate butyrate, phenoxy, poly(vinyl pyrrolidone), poly(vinyl pyrrolidone)-co-poly(vinyl acetate), poly(ethylene oxide), and combinations thereof.

Support for the amendments may be found in Applicants' specification at, for example, Table 1, pages 20-25, and page 30, lines 3-19.

Claims 10, 56, 75, and 79 are amended to recite that the miscible polymer blend can include a polyurethane and at least one miscible hydrophilic polymer selected from the group consisting of a polyurethane, a polyvinyl alcohol, a poly(alkylene ether), a polyvinyl pyridine, a polyvinyl pyrrolidone, a polyacrylamide, a polyvinyl pyrrolidone/polyvinyl acetate copolymer, a sulfonated polystyrene, a polyvinyl pyrrolidone/polystyrene copolymer, a polysaccharide, a xanthan, a hydrophilic cellulose derivative, a hyaluronic acid, a hydrophilic polyacrylate, a hydrophilic polymethacrylate, a DNA or analog thereof, an RNA or analog thereof, heparin, a chitosan, a polyethylene imine, a polyacrylamide, an amine-containing polymer, and combinations thereof.

Support for the amendments may be found in Applicants' specification at, for example, page 32, lines 11-19.

Claims 75, 78, 79, and 80 are amended to recite that the active agent has a solubility parameter.

Support for the amendments may be found in Applicants' specification at, for example, from page 18, line 28 through page 19, line 5 and Table 1, pages 20-25.


## The 35 U.S.C. §102 Rejections

Claims 1-18, 20-75, and 78-88 stand rejected under 35 U.S.C. §102(e) as being anticipated by Sirhan *et al.* (U.S. 2002/0082679 A1). Claims 1-18, 20-75, and 78-88 stand rejected under 35 U.S.C. §102(b) as being anticipated by Hossainy *et al.* (U.S. 6,153,252). Claims 1-18, 20-75, and 78-88 stand rejected under 35 U.S.C. §102(b) as being anticipated by Whitbourne *et al.* (U.S. 6,110,483). Applicants respectfully traverse the rejections.

Claims 1, 10, 20, 32, 56, 63, 75, 78, 79, and 80 are independent. Each of the remaining claims depends, directly or indirectly, from one of the independent claims. Thus,

remarks that refer to one or more independent claims apply equally to any claim that depends from a referenced independent claim.

Each independent claim is directed to methods that include forming a miscible polymer blend particularly suited for use in an active agent delivery system. Each independent claim recites in some form—e.g., "selecting a second polymer" or "a second polymer selected" to be miscible with another polymer—the concept of selecting a second polymer for inclusion in the miscible polymer blend based on certain specified criteria. In particular, the second polymer is selected to be miscible with the first polymer. For brevity in the remarks that follow, reference to any one of: a second polymer "selected" to be, or "selecting" a second polymer to be (or any other equivalent phrase), miscible with another component of the miscible polymer blend includes the other. The second miscible polymer is selected from the groups recited in Applicants' claims (e.g., claim 1 and claim 10). Further, the second miscible polymer is selected so that the difference between at least one solubility parameter of each of at least two polymers is no greater than about 3 $J^{1/2}/cm^{3/2}$. For brevity, reference in the following remarks to the second polymer being selected based on "criteria recited in Applicants' claims" or an equivalent phrase refers to (a) miscibility with the first polymer, (b) selected from the recited types of polymers, and (c) so that the difference between at least one solubility parameter of the first polymer and at least one solubility parameter of the second polymer is no greater than about 3 $J^{1/2}/cm^{3/2}$. Also, "the recited difference in solubility parameters" or an equivalent refers to the difference between at least one solubility parameter of the first polymer and at least one solubility parameter of the second polymer being no greater than about 3 $J^{1/2}/cm^{3/2}$.

**Claims 1-18, 20-75, and 78-88 are not anticipated under 35 U.S.C. §102(b) by Hossainy *et al.* (U.S. Patent No. 6,153,252)**

M.P.E.P. §2131 states, "A claim is anticipated only if each and every element as set forth in the claim is found, either expressly or inherently described, in a single prior art reference."

Hossainy *et al.* teach processes for coating stents. Although Hossainy *et al.* teach certain types of polymers that encompass the polymers from which polymers of Applicants' miscible polymer blend may be selected, Hossainy *et al.* list over 30 classes of polymers that encompass innumerable species of polymers (arguably thousands if not hundreds of thousands or more) at columns 4 and 5. This list includes references to a handbook (The Handbook of Biodegradable Polymers), an encyclopedia (The Encyclopedia of Polymer Science), journal articles (in Polymer Preprints and Journal of Biomaterials Research), and patents (16 patents).

The Examiner asserts that Hossainy *et al.* teach "the mixtures of the same polymers and active ingredients as applicants [sic] claimed invention, therefore it is <u>inherent</u> that the same polymers and actives will have the same solubility parameters." (Office Action, page 5, emphasis added). Applicants respectfully disagree.

Inherency applies only if the missing element "is necessarily present in the thing described in the reference, and that it would be so recognized by persons of ordinary skill." *Cont'l Can Co. v. Monsanto Co.*, 948 F.2d 1264, 1268, 20 USPQ2d 1746, 1749 (Fed. Cir. 1991). "Inherent anticipation requires that the missing descriptive material is 'necessarily present,' not merely probably or possibly present, in the prior art." *Trintec Indus., Inc. v. Top-U.S.A. Corp.*, 295 F.3d 1292, 1295, 63 USPQ2d 1597, 1599 (Fed. Cir. 2002) (quoting *In re Robertson*, 169 F.3d 743, 745, 49 USPQ2d 1949, 1950-51 (Fed. Cir. 1999)). *Roscoe, Inc. v, Mirror Lite Co.*, 304 F.3d 1373, 1380, 64 USPQ2d 1676, 1680 (Fed. Cir. 2002). Applicants respectfully submit that the miscible polymer blends recited in Applicants' claims—i.e., blends formed from polymers

selected based on criteria recited in Applicants' claims—are not necessarily present in the mixtures of the broad classes of polymers listed in Hossainy *et al.*

Hossainy *et al.* describe classes and/or types of polymers that are identified in Applicants' specification as classes and/or types from which polymers may be selected to form the particular subpopulation of miscible polymer blends recited in Applicants' claims. Hossainy *et al.*, however, fail to expressly or inherently set forth the specific polymer combinations recited in the claims. The Examiner seems to base the rejection on the assumption that all polymers of one class or type (e.g., polymethacrylates, polyurethanes, hydrophobic cellulose derivatives, etc.) have the same solubility parameter so that selecting <u>any</u> polymers within the recited types or classes of polymers will <u>necessarily</u> result in a polymer combination having the recited difference in solubility parameter. This is incorrect.

Applicants submit herewith the declaration of Christopher M. Hobot (the "Declaration"). Paragraph 3 of the Declaration lists solubility parameters of selected polymethacrylates. The solubility parameter of a polymethacrylate polymer can vary significantly with respect to the recited difference in solubility parameter. For example, poly(t-butyl methacrylate) has a solubility parameter of 17.0 while poly(methyl methacrylate) possesses a solubility parameter of 22.4. Thus, the mere listing in Hossainy *et al.* of general classes of polymers that includes classes similarly identified in Applicants' specification is insufficient to <u>necessarily</u>—i.e., inherently—teach the specific subpopulations of combinations recited in Applicants' claims.

For example, the Examiner asserts that Hossainy *et al.* specifically list polyurethanes, polyamides, polyesters, polymethacrylates, polyolefins, ethylene methyl methacrylate copolymers, various hydrophilic celluloses, etc. (Office Action, page 5). The Examiner further states, "As mentioned numerous times in actions in the past and again herein both the Hossainey [sic] and Whitbourne references clearly teach the same first and second polymers claimed by applicants." (Office Action, page 10).

Hossainy *et al.* may teach some of the same <u>classes</u> of polymers (e.g., polyurethanes and methacrylates) from which the first and second polymer may be selected. Hossainy *et al.* fail, however, to teach the specific individual polymers from among the classes listed in the Office Action that one should select so that the second polymer will be miscible with the first polymer and possess the recited <u>difference in solubility parameter</u> with respect to the first polymer. For example, the combination of a polymethacrylate and a polyurethane does not <u>necessarily</u> result in a polymer blend in which the difference between at least one solubility parameter of the polymethacrylate and at least one solubility parameter of the polyurethane is no greater than about 3 $J^{1/2}/cm^{3/2}$.

Paragraph 3 of the Declaration lists solubility parameters of selected exemplary members of the classes of polymethacrylates and polyurethanes. The solubility parameter of various exemplary polymethacrylates is shown to vary from 17.0 (for poly(t-butyl methacrylate)) to 22.4 (for poly(methyl methacrylate)). Also, depending upon the particular polyurethane and whether the polyurethane is dominated by the hard segment or soft segment of the polymer— neither of which is specified in Hossainy *et al.*—the solubility parameter of selected exemplary polyurethanes can vary: 22.5 to 24.3 for hard segment-dominated poly(carbonate urethane) and hard segment-dominated poly(ether urethane), 18.9 for soft segment-dominated poly(carbonate urethane), and a range of 17.0 to 19.6 for soft segment-dominated poly(ether urethane). Paragraph 6 of the Declaration explains that the ranges of solubility parameters listed in Paragraph 3 are exemplary values; Paragraph 3 is not intended to provide an exhaustive list of possible polyurethanes and solubility parameters. Also, Paragraph 6 of the Declaration explains that the ranges in solubility parameter depend, at least in part, upon the composition of a given polyurethane. Consequently, depending upon the particular combination of polyurethane and polymethacrylate selected, and whether the polyurethane is hard segment-dominated or soft segment-dominated, the difference in solubility parameter may be, in some cases, no greater than about 3 $J^{1/2}/cm^{3/2}$ or, in other cases, may be greater than about 3 $J^{1/2}/cm^{3/2}$.

For example, a blend of soft segment-dominated poly(carbonate urethane (solubility parameter = 18.9) and poly(ethyl methacrylate) (solubility parameter = 18.5) is less than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta$ = 0.4). However, a blend of soft segment-dominated poly(carbonate urethane and poly(methyl methacrylate) (solubility parameter = 22.4) is greater than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta$ = 3.5).

As another example, a blend of hard segment-dominated poly(ether urethane) (solubility parameter = 22.5 to 24.3) and poly(methyl methacrylate) is less than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta$ = 0.1 to 1.9), but a blend of hard segment-dominated poly(ether urethane) and poly(butyl methacrylate) (solubility parameter = 18.1) is greater than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta$ = 4.4 to 6.2).

Paragraph 5 of the Declaration explains that a person of ordinary skill in the art understands that the solubility parameter of the dominant segment in the continuous phase of the miscible polymer blend is the solubility parameter of a segmented polymer that should be considered when calculating differences in solubility parameter between the segmented polymer and either a second polymer or an active agent.

The teaching of Hossainy *et al.* is insufficient to <u>necessarily</u> result in the specific miscible polymer blends that are recited in Applicants' claims. In particular, Hossainy *et al.* do not distinguish between hydrophilic and hydrophobic polyurethanes. Also, Hossainy *et al.* do not distinguish between hard segment-dominated and soft segment dominated polymers. In contrast, Applicants' specification provides specific teaching directing one skilled in the art to select polymers so that the difference in solubility parameter between the polymers is no greater than about 3 $J^{1/2}/cm^{3/2}$ (Specification, page 18, line 28 through page 19, line 4), guidance for determining the solubility parameter of a compound (Specification, page 19, lines 6-23), the solubility parameters of some exemplary compounds (Table 1, pages 20-25), and considerations of hard segments and soft segments of segmented polymers (e.g., Specification, page 11, lines 3-32 and page 19, lines 6-8). Because a mixture of a polyurethane and a polymethacrylate can result in a blend of polymers possessing a difference in solubility parameter of greater than 3

$J^{1/2}/cm^{3/2}$, such a mixture does not <u>necessarily</u> result in a polymer blend possessing the recited difference in solubility parameters. Thus, contrary to the position set forth in the Office Action, Hossainy *et al*. do not inherently teach the polymer blends recited in Applicants' claims.

For at least this reason, Applicants submit that claims 1-18, 20-75, and 78-88 are novel over Hossainy *et al*. Applicants therefore respectfully request that the rejection be withdrawn.

In addition, Applicants' claims recite the cognitive and discretionary step of selecting the second polymer to be miscible with the first polymer <u>and</u> to possess a solubility parameter that differs from the solubility parameter of the first polymer by no greater than 3 $J^{1/2}/cm^{3/2}$. This cognitive and discretionary portion of the polymer selection process is neither taught nor suggested in Hossainy *et al*. Accordingly, if this feature is properly considered during examination of Applicants' claims, then Hossainy *et al*. cannot anticipate Applicants' claims.

However, the Examiner ignores any "selecting" step as allegedly being a mental process or abstract idea, and therefore asserts that this feature—e.g., "selecting a second polymer" or "a second polymer selected" to be miscible with the first polymer—can be ignored during examination.

M.P.E.P. §2106(IV)(C)(2) states that claims including a mental process or abstract idea are, indeed, eligible for patent protection if they are a <u>practical application</u> of the mental process or an abstract idea. A claimed invention is directed to a practical application of a mental process or abstract idea when it "transforms" an article or physical object to a different state or thing. Applicants respectfully submit that the subject matter recited in Applicants' claims provides a material transformation. Accordingly, under the analysis set forth in M.P.E.P. §2106(IV)(C)(2), selecting the second polymer according to the criteria recited in the claims is, indeed, eligible for patent protection and the rejections of Applicants' claims based on ignoring this feature of Applicants' claims is improper.

In the present application, Applicants' claimed methods transform the individual polymers into a miscible polymer blend. The miscible polymer blend and active agent are combined to form an active agent delivery system. During delivery of the active agent, the formed system is, necessarily transformed as active agent is released to the body, which is itself chemically and/or physically transformed by the release of the active agent. Selecting the second polymer in relation to the first polymer and based on the recited criteria contributes to the controlled delivery of the active agent. It provides particular properties to the resultant combination of components in the composition. For at least these reasons, each of Applicants' independent claims, when considered as a whole, results in the physical transformation of matter influenced at least in part by selecting the second polymer in relation to the first polymer and the criteria recited in Applicants' claims. Selecting the second polymer in this way is therefore a patentable distinction over the prior art and must be considered in relation to the cited documents.

Therefore, because practicing Applicants' claims results in a transformation of matter, selecting the second polymer in relation to the first polymer and according to the criteria recited in the claims is, indeed, a patentable difference in view of the prior art. For at least this reason, selecting the second polymer as recited in Applicants' claims must be considered when examining Applicants' claims. Hossainy *et al.* fail to teach, expressly or inherently, a method that includes forming a miscible polymer blend by the conscious, deliberate, and discretionary step of selecting a second polymer from among the recited group of suitable second polymers based on miscibility with, and the recited difference in solubility parameter compared to, a polymer from among the recited groups of suitable first polymers.

The Examiner disagrees with Applicants' remarks but provides no authority for the position set forth. The Office Action asserts, "[A]pplicants [sic] attempt of limiting the independent claims so the second polymer is **selected** to be miscible with the first polymer is a **mental process or abstract idea** and is not a patentable difference in view of the prior art."

(Office Action, page 13, emphasis in original). The Examiner fails to provide any authority for disregarding M.P.E.P. §2106(IV)(C)(2).

The Examiner continues, further asserting that selecting the second polymer so that the polymers in the blend possess solubility parameters within the recited difference of solubility parameters can be reduced to a mathematical formula. (Office Action, page 14). The Examiner therefore concludes that he "cannot consider it as a patentable distinction." *Id.* This position is untenable.

First, by the Examiner's logic, any feature of a claim that includes a number cannot be considered as a patentable distinction because any claim feature reciting a number can be reduced to a mathematical formula. For example, the length ($l$), height ($h$), and/or width ($w$) of a component of a mechanical device can be reduced to, for example, $l = x$, $h > y$, $w \leq z$, etc. Thus, the mere fact that a feature of Applicants' claims can be reduced to a mathematical formula does not mean that the feature can be disregarded during examination.

Second, the position stated by the Examiner directly contradicts established Federal Circuit caselaw and M.P.E.P. §2106(IV)(C). M.P.E.P. §2106(IV)(C) states:

> While abstract ideas, natural phenomena, and laws of nature are not eligible for patenting, methods and products employing abstract ideas, natural phenomena, and laws of nature to perform a real-world function may well be. In evaluating whether a claim meets the requirements of section 101, the claim must be considered as a whole to determine whether it is for a particular application of an abstract idea, natural phenomenon, or law of nature, and not for the abstract idea, natural phenomenon, or law of nature itself.

(emphasis added). Applicants' claims are not directed toward the abstract idea $|x - y| \leq 3$ itself, where each of $x$ and $y$ is a solubility parameter of a polymer that is a candidate for inclusion in the recited miscible polymer blend. Rather, Applicants' claims are directed to a method that is a particular application of the idea in order to prepare miscible polymer blends having certain practical properties. In evaluating whether the claim meets the requirements of §101, the claim must be considered as a whole. There is simply no authority for the Examiner to utterly disregard a recited feature of Applicants' claims.

Applicants' position is supported by the Federal Circuit in *In re Bilski*, 88

USPQ2d 1385 (2008). In *In re Bilski*, the court thoroughly summarized the state of law

regarding patent-eligible subject matter.

Procedurally, the Federal Circuit stated definitively that the Examiner's disregard

for Applicants' "selecting" feature as being patent-ineligible subject matter is inappropriate.

Referring to guidance provided by the U.S. Supreme Court, the Federal Circuit noted:

> [T]he Court has made clear that it is inappropriate to determine the patent-eligibility of a
> claim <u>as a whole</u> based on whether <u>selected limitations</u> constitute patent-eligible subject
> matter. [citations omitted]. After all, even though a fundamental principle itself is not
> patent-eligible, processes incorporating a fundamental principle may be patent-eligible.
> Thus, <u>it is irrelevant that any individual step or limitation of such processes by itself would
> be unpatentable under §101</u>. [citations omitted]

88 USPQ2d 1385, 1394 (emphasis added). Thus, the Examiner's stated approach to examining

Applicants' claims is improper. The Examiner must consider the claim as a whole, including

features that the Examiner may consider to be patent-ineligible on their own.

Moreover, the decision in *In re Bilski* makes clear that Applicants' claims do,

indeed, recite patent-eligible subject matter. In *In re Bilski*, the Federal Circuit cited the U.S.

Supreme Court in *Diamond v. Diehr*, 450 U.S. 175, 185 [209 USPQ 1] (1981) stating that "a

claim is not a patent-eligible 'process' if it claims 'laws of nature, natural phenomena, [or]

abstract ideas.'" The Office Action refers to the same portion of *Diamond v. Diehr* in support of

the position that Applicants' claims are patent-ineligible subject matter. The Federal Circuit,

however, continued its analysis of the Supreme Court decision in *Diamond v. Diehr* as follows:

> The *Diehr* Court stated: "[W]hen a claim containing a mathematical formula implements
> or applies that formula in a *structure* or process which, <u>when considered as a whole</u>, is
> performing a function which the patent laws were designed to protect (*e.g., transforming
> or reducing an article to a different state or thing*), then the claim satisfies the
> requirements of §101."

88 USPQ2d at 1393, fn 12 (italicized emphasis in original, underlined emphasis added). Thus,

the Federal Circuit distinguishes a patent-ineligible process claim that seeks to wholly pre-empt

application of a mathematical formula from a patent-eligible process claim that may employ the

mathematical formula, but transforms matter (e.g., individual polymers) into a different state or thing (e.g., a miscible blend of polymers).

The Federal Circuit further noted that while "a mathematical algorithm alone is unpatentable because mathematical relationships are akin to a law of nature, the Court [the U.S. Supreme Court in *Diamond v. Diehr*] nevertheless held that the claimed process was patent-eligible subject matter, stating:

> [The inventors] do not seek to patent a mathematical formula. Instead, they seek patent protection for a process of curing synthetic rubber. Their process admittedly employs a well-known mathematical equation, but *they do not seek to pre-empt the use of that equation.* Rather, they seek only to foreclose from others the use of that equation in conjunction with all of the other steps in their claimed process."

88 USPQ2d at 1389-1390 (emphasis in original). The court further acknowledged that while a claim drawn to a fundamental principle is unpatentable, "an *application* of a law of nature or mathematical formula to a known structure or process may well be deserving of patent protection." 88 USPQ2d at 1390 (emphasis in original).

Applicants' claims do not seek to pre-empt all use of the equation $|x - y| \leq 3$. Instead, Applicants claim methods that include selecting polymers for inclusion in a miscible polymer blend based on the similarity of a measurable and/or calculable characteristic of the polymers. The methods include combining the selected polymers, thereby transforming the individual polymers to a chemical blend of the polymers. In *In re Bilski*, the Federal Circuit states:

> [i]t is virtually self-evident that <u>a process for a chemical or physical transformation</u> of *physical objects or substances* is patent-eligible subject matter.

88 USPQ2d at 1396 (italicized emphasis in original, underlined emphasis added). Applicants' claims involve the chemical transformation of individual polymers to a miscible polymer blend, the transformation of a miscible polymer blend to an active agent delivery system. In use, release of the active agent further chemically transforms both the active agent delivery system and the body into which the active agent is delivered. Thus, Applicants' claims embody a process for

chemical transformation of substances (e.g., individual polymers, the miscible polymer blend, the active agent delivery system, and/or the body into which the active agent is released) and are, according to the Federal Circuit in *In re Bilski*, patent-eligible subject matter.

Hossainy *et al.* fail to teach, expressly or inherently, the cognitive and discretionary step of selecting the second polymer to be miscible with the first polymer <u>and</u> to possess a solubility parameter that differs from the solubility parameter of the first polymer by no greater than 3 $J^{1/2}/cm^{3/2}$. Thus, Hossainy *et al.* cannot anticipate Applicants' claims.

Therefore, for at least these reasons, Applicants submit that claims 1-18, 20-75, and 78-88 are novel over Hossainy *et al.* and request that the rejection be withdrawn.

**Claims 1-18, 20-75, and 78-88 are not anticipated under 35 U.S.C. §102(b) by Whitbourne *et al.* (U.S. Patent No. 6,110,483)**

Whitbourne *et al.* teach polymer coatings for medical devices. Whitbourne *et al.* teach more than a dozen classes of polymers in columns 5 and 6, which, as in Hossainy *et al.*, include innumerable species of polymers. Whitbourne *et al.* also includes polymers discussed in two encyclopedias (Concise Encyclopedia of Polymer Science and Engineering, and Kirk-Othmer Concise Encyclopedia of Chemical Technology).

The Examiner asserts that Whitbourne *et al.* teach "the mixtures of the same polymers and active ingredients as applicants [sic] claimed invention, therefore it is <u>inherent</u> that the same polymers and actives will have the same solubility parameters." (Office Action, page 7, emphasis added). Applicants respectfully disagree.

As noted above with respect to the teaching of Hossainy *et al.*, inherent anticipation requires that the missing descriptive material is 'necessarily present,' not merely probably or possibly present, in the prior art. Applicants respectfully submit that the miscible polymer blends recited in Applicants' claims—i.e., blends formed from polymers that are selected based on criteria recited in Applicants' claims—are not necessarily present in the

mixtures of the broad classes of polymers listed in Whitbourne *et al.* and, therefore, Whitbourne *et al.* cannot anticipate Applicants' claims.

Whitbourne *et al.* describe classes and/or types of polymers that are identified in Applicants' specification as classes and/or types from which polymers may be selected to form the particular subpopulation of miscible polymer blends recited in Applicants' claims. Whitbourne *et al.*, however, fail to expressly or inherently set forth the specific polymer combinations recited in the claims. The Examiner again seems to base the rejection on the assumption that all polymers of one class or type have the same solubility parameter so that selecting any polymers within the recited types or classes of polymers will necessarily result in a polymer combination having the recited difference in solubility parameter. As noted above with respect to Hossainy *et al.*, the mere listing in Whitbourne *et al.* of general classes of polymers that includes classes similarly identified in Applicants' specification is insufficient to necessarily—i.e., inherently—teach the specific subpopulations of combinations recited in Applicants' claims.

The Examiner asserts that Whitbourne *et al.* specifically list polyurethanes, acrylic polymers, methacrylic polymers, vinyl acetal polymers, polyethers, PVP (polyvinyl pyrrolidone), epoxy polymers, etc. (Office Action, page 7). Whitbourne *et al.* fail to teach the specific individual polymers from among the classes listed in the Office Action that one should select so that the second polymer will be miscible with the first polymer and possess the recited difference in solubility parameter with respect to the first polymer.

The examples provided above in the discussion of Hossainy *et al.* applies equally to the teaching of Whitbourne *et al.*: the combination of a polymethacrylate and a polyurethane does not necessarily result in a polymer blend in which the difference between at least one solubility parameter of the polymethacrylate and at least one solubility parameter of the polyurethane is no greater than about 3 $J^{1/2}/cm^{3/2}$. An exemplary blend of soft segment-dominated poly(carbonate urethane) and poly(ethyl methacrylate) is less than about 3 $J^{1/2}/cm^{3/2}$

($\Delta = 0.4$). However, an exemplary blend of soft segment-dominated poly(carbonate urethane) and poly(methyl methacrylate) is greater than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta = 3.5$). As another example, an exemplary blend of hard segment-dominated poly(ether urethane) and poly(methyl methacrylate) is less than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta = 0.1$ to 1.9), but an exemplary blend of hard segment-dominated poly(ether urethane) and poly(butyl methacrylate) is greater than about 3 $J^{1/2}/cm^{3/2}$ ($\Delta = 4.4$ to 6.2).

The teaching of Whitbourne *et al.* is insufficient to <u>necessarily</u> result in the specific miscible polymer blends that are recited in Applicants' claims. In contrast, Applicants' specification provides specific teaching directing one skilled in the art to select polymers so that the difference in solubility parameter between the polymers is no greater than about 3 $J^{1/2}/cm^{3/2}$ (Specification, page 18, line 28 through page 19, line 4), guidance for determining the solubility parameter of a compound (Specification, page 19, lines 6-23), and the solubility parameters of some exemplary compounds (Table 1, pages 20-25). Because a mixture of a polyurethane and a polymethacrylate can result in a blend of polymers possessing a difference in solubility parameter of greater than 3 $J^{1/2}/cm^{3/2}$, such a mixture does not <u>necessarily</u> result in a polymer blend possessing the recited difference in solubility parameters. Thus, contrary to the position set forth in the Office Action, Whitbourne *et al.* do not inherently teach the polymer blends recited in Applicants' claims.

Also, Whitbourne *et al.*, like Hossainy *et al.*, fail to teach, expressly or inherently, the cognitive and discretionary step of selecting the second polymer to be miscible with the first polymer <u>and</u> to possess a solubility parameter that differs from the solubility parameter of the first polymer by no greater than 3 $J^{1/2}/cm^{3/2}$. Thus, Whitbourne *et al.* cannot anticipate Applicants' claims.

For at least these reasons, Applicants submit that claims 1-18, 20-75, and 78-88 are novel over Whitbourne *et al.* Applicants therefore respectfully request that the rejection be withdrawn.

**Claims 1-18, 20-75, and 78-88 are not anticipated under 35 U.S.C. §102(e) by Sirhan**
**_et al._ (U.S. Patent Application Publication No. US 2002/0082679 A1)**

Sirhan _et al._ teach luminal prosthetic devices that allow for controlled release of a therapeutic agent (Sirhan _et al._, Abstract). More than a dozen classes of suitable polymers are listed in paragraphs [0119] and [0120], including "mixtures, copolymers, and combinations thereof" for each set of polymers.

The Examiner asserts that Sirhan _et al._ teach "the mixtures of the same polymers and active ingredients as applicants [sic] claimed invention, therefore it is <u>inherent</u> that the same polymers and actives will have the same solubility parameters." (Office Action, page 3, emphasis added). Applicants respectfully disagree.

As noted above with respect to the teachings of Hossainy _et al._ and Whitbourne _et al._, inherent anticipation requires that the missing descriptive material is 'necessarily present,' not merely probably or possibly present, in the prior art. Applicants respectfully submit that the miscible polymer blends recited in Applicants' claims—i.e., blends formed from polymers that are selected based on criteria recited in Applicants' claims—are not necessarily present in the mixtures of the broad classes of polymers listed in Sirhan _et al._ and, therefore, Sirhan _et al._ cannot anticipate Applicants' claims.

Sirhan _et al._ describe classes and/or types of polymers that are identified in Applicants' specification as classes and/or types from which polymers may be selected to form the particular subpopulation of miscible polymer blends recited in Applicants' claims. Sirhan _et al._, however, fail to expressly or inherently set forth the specific polymer combinations recited in the claims. The Examiner yet again seems to base the rejection on the assumption that all polymers of one class or type have the same solubility parameter so that selecting <u>any</u> polymers within the recited types or classes of polymers will <u>necessarily</u> result in a polymer combination having the recited difference in solubility parameter. As noted above with respect to Hossainy _et_

*al.* and Whitbourne *et al.*, the mere listing in Sirhan *et al.* of general classes of polymers that includes classes similarly identified in Applicants' specification is insufficient to necessarily— i.e., inherently—teach the specific subpopulations of combinations recited in Applicants' claims.

The Examiner asserts that Sirhan *et al.* specifically list cellulose acetate butyrate (CAB), polyethylene vinyl acetate (PEVA), polyurethane, polycarbonates, poly(methyl methacrylate) and the like and mixture and combinations thereof. (Office Action, pages 2-3). Sirhan *et al.* fail to teach the specific individual polymers from among the classes listed in the Office Action that one should select so that the second polymer will be miscible with the first polymer and possess the recited difference in solubility parameter with respect to the first polymer.

For example, Paragraph 3 of the Declaration lists solubility parameters of poly(methyl methacrylate) and selected exemplary members of the class of polyurethanes. Depending upon the particular polyurethane—in these examples, poly(carbonate urethane) and poly(ether urethane), but others are possible—and the extent to which the exemplary polyurethane is dominated by the hard segment or the soft segment, the difference in solubility parameter of poly(methyl methacrylate) and the exemplary polyurethane can be 0.1 to 1.9 (entirely within Applicants' recited range), 3.5 (outside of Applicants' recited range), or vary from 2.8 to 5.4 (some within and some outside Applicants' recited range). Thus, the mere description of combinations of poly(methyl methacrylates) and polyurethanes does not necessarily result in miscible polymer blends that are within the subpopulation of polymer blends recited in Applicants' claims.

As another example, Paragraph 3 of the Declaration provides the solubility parameters for selected exemplary members of the classes of polyurethanes (as previously discussed) and polycarbonates. The listed solubility parameters identify certain combinations having the recited difference in solubility parameters (e.g., poly(hexyl methylene carbonate) and the exemplary soft segment-dominated polyurethanes; poly(bis phenol A carbonate) and the

exemplary hard segment-dominated polyurethanes), but others that do not (e.g., poly(hexyl methylene carbonate) and the exemplary hard segment-dominated polyurethanes; poly(bis phenol A carbonate) and the exemplary soft segment-dominated polyurethanes). Thus, the mere description of combinations of polyurethanes and polycarbonates does not <u>necessarily</u> result in miscible polymer blends that are within the subpopulation of polymer blends recited in Applicants' claims.

  The teaching of Sirhan *et al.* is insufficient to <u>necessarily</u> result in the specific miscible polymer blends that are recited in Applicants' claims. In contrast, Applicants' specification provides specific teaching directing one skilled in the art to select polymers so that the difference in solubility parameter between the polymers is no greater than about 3 $J^{1/2}/cm^{3/2}$ (Specification, page 18, line 28 through page 19, line 4), guidance for determining the solubility parameter of a compound (Specification, page 19, lines 6-23), and the solubility parameters of some exemplary compounds (Table 1, pages 20-25). Because a mixture or combination of, for example, poly(methyl methacrylate) and a polyurethane or a mixture or combination of, for example, a polycarbonate and a polyurethane can result in a blend of polymers possessing a difference in solubility parameter of greater than 3 $J^{1/2}/cm^{3/2}$, such a mixture does not <u>necessarily</u> result in a polymer blend possessing the recited difference in solubility parameters. Thus, contrary to the position set forth in the Office Action, Sirhan *et al.* do not inherently teach the polymer blends recited in Applicants' claims.

  Also, Sirhan *et al.*, like Hossainy *et al.* and Whitbourne *et al.*, fail to teach, expressly or inherently, the cognitive and discretionary step of selecting the second polymer to be miscible with the first polymer <u>and</u> to possess a solubility parameter that differs from the solubility parameter of the first polymer by no greater than 3 $J^{1/2}/cm^{3/2}$. Thus, Sirhan *et al.* cannot anticipate Applicants' claims.

For at least these reasons, Applicants submit that claims 1-18, 20-75, and 78-88 are novel over Sirhan *et al.* Applicants therefore respectfully request that the rejection be withdrawn.

### Replies to the Examiner's Response to Arguments

In their response filed June 20, 2008, Applicants noted, in part, that none of Sirhan *et al.*, Hossainy *et al.*, or Whitbourne *et al.* provides disclosure that would support a hypothetical claim similar to Applicants' claims. Applicants noted that with regard to the written description requirement of 35 U.S.C. §112, first paragraph, M.P.E.P. §2163.05 states:

> The introduction of claim changes which involve narrowing the claims by introducing elements or limitations which are not supported by the as-filed disclosure is a violation of the written description requirement of 35 U.S.C. 112, first paragraph. See, e.g., *Fujikawa v. Wattanasin*, 93 F.3d 1559, 1571, 39 USPQ2d 1895, 1905 (Fed. Cir. 1996) (a "laundry list" disclosure of every possible moiety does not constitute a written description of every species in a genus because it would not "reasonably lead" those skilled in the art to any particular species).

An amendment introducing one or more claims comparable to Applicants' claims into any one of the cited documents would require introducing narrowing limitations or elements unsupported by the disclosure of the cited document. With respect to a hypothetical claim comparable to Applicants' claims, the disclosures of the cited documents amount to no more than a laundry list of possible classes of polymers, members of which may be combined. These disclosures, however, fail to describe the particular subpopulation—i.e., particular species—of polymer combination selected based on the criteria recited in Applicants' claims. Consequently, a claim comparable to Applicants' claims, if added to any of the cited documents, would have been rejected as lacking written description support.

The Examiner responded, in part, by stating that the polymer blends recited in Applicants' pending claims are claimed in Sirhan *et al.*, which, as an allowed U.S. patent is considered valid and, therefore, the claims of Sirhan *et al.* are fully supported by its disclosure.

(Office Action, page 10). Applicants' respectfully disagree with the Examiner's position. The specific subpopulation of polymer blends <u>are not</u> claimed or described by Sirhan *et al*. Paragraph [0053] and claim 126 (specifically identified at page 3 of the Office Action as providing description of Applicants' polymer blends) provide no more than a laundry list of polymer classes. Thus, Applicants maintain the position that an attempt to add to Sirhan *et al*. a hypothetical claim that narrows the scope of blends recited in Sirhan *et al*. claim 126 to only those polymer blends that possess the specific criteria recited in Applicants' claims would be rejected as failing to satisfy the written description requirement of 35 U.S.C. 112, first paragraph for introducing claim changes that involve narrowing the claims by introducing elements or limitations which are not supported by the as-filed disclosure. Description for such a hypothetical claim is lacking in Sirhan *et al*. for at least all of the reasons set forth above in connection with the rejection of Applicants' claims 1-18, 20-75, and 78-88 as being anticipated by Sirhan *et al*.

The Examiner also responds by asserting that Applicants' disclosure is similarly broad to the disclosures of the cited documents in the numbers and types of polymers that can be blended. (Office Action, page 11). The argument advanced by Applicants regarding the lack of written description in the cited documents for a claim comparable to Applicants' claims is not directed at descriptions of polymers that may be merely blended. Applicants submit that the cited documents fail to describe, expressly or inherently, blends of polymers whose solubility parameters differ by no more than 3 $J^{1/2}/cm^{3/2}$. Consequently, the disclosures of the cited documents fail to convey to one skilled in the art possession of the particular subpopulation of polymer blends recited in Applicants' claims. Applicants have noted throughout prosecution that the claims recite a particular subset of polymer blends and that the particular subset of polymer blends recited in Applicants' claims are neither expressly nor inherently described in the cited documents.

Applicants acknowledge the Examiner's assertion that Applicants' disclosure describes many classes of polymers from which polymers for the recited miscible polymer blends may be selected. However, Applicants' disclosure provides <u>additional guidance that is not found in any of the cited documents</u>. Applicants describe the desirability of selecting polymers so that the difference between at least one solubility parameter of each of at least two polymers is no greater than about 3 $J^{1/2}/cm^{3/2}$. (Specification, page 18, line 28 through page 19, line 5). Moreover, Applicants' disclosure teaches how one can determine the solubility parameter of a compound <u>and</u> provide solubility parameter values for many exemplary compounds (Specification, page 19, line 6 through page 25, including Table 1). <u>This</u> teaching is utterly absent in the cited documents and provides written description support for the particular miscible polymer blends recited in Applicants' claims.

Also in their response filed June 20, 2008, Applicants submitted that solubility parameter is a characteristic of individual compounds and/or polymers analogous to molecular weight, degree of crosslinking, glass transition temperature, etc. Thus, individual compounds within a class of polymers—e.g., polyurethanes—can have solubility parameters that vary significantly with respect to the difference in solubility parameter recited in Applicants' claims. Applicants argued, therefore, that the Examiner's position that mere disclosure in the cited documents that mixtures or combinations of, for example, polyurethanes and polymethacrylates would inherently possess the recited difference in solubility parameter is inaccurate—many combinations of, for example, a polyurethane and a polymethacrylate can result in a combination in which the polymers possess solubility parameters that exceed the recited difference in solubility parameter.

The Examiner responded in the Office Action by stating that consideration of molecular weight, degree of crosslinking, and glass transition temperature was not necessary "since these parameters are not within the claims. The examiner can only search for the claimed subject matter." (Office Action, page 12).

As reiterated above, Applicants understand that molecular weight, degree of crosslinking, and glass transition temperature are not universally recited in the claims (molecular weights of certain active agents are recited in certain claims, but that is beside the point of the instant remarks). These characteristics were used as familiar examples of characteristics—analogous to solubility parameter—of compounds and/or polymers that can vary between individual compounds and/or polymers within a class.

Applicants do not request or expect that examination be based on features that are not recited in the claims. Applicants reasonably request only that the claims are examined based on the features recited in the claims. Applicants note that the difference in solubility parameter is expressly recited in each of the independent claims.

In summary, Applicants submit that claims 1-18, 20-75, and 78-88 are novel over Sirhan *et al.* and request that the rejection of claims 1-18, 20-75, and 78-88 under 35 U.S.C. §102(b) as being anticipated by Sirhan *et al.* be withdrawn. Further, Applicants submit that claims 1-18, 20-75, and 78-88 are novel over Hossainy *et al.* and request that the rejection of claims 1-18, 20-75, and 78-88 under 35 U.S.C. §102(b) as being anticipated by Hossainy *et al.* be withdrawn. Applicants further submit that claims 1-18, 20-75, and 78-88 are novel over Whitbourne *et al.* and request that the rejection of claims 1-18, 20-75, and 78-88 under 35 U.S.C. §102(b) as being anticipated by Whitbourne *et al.* be withdrawn.

**The 35 U.S.C. §103 Rejections**

Claims 1-18, 20-75, and 78-88 stand rejected under 35 U.S.C. §103(a) as being unpatentable over Sirhan *et al.* (U.S. 2002/0082679 A1). Claims 1-18, 20-75, and 78-88 further stand rejected under 35 U.S.C. §103(a) as being unpatentable over Hossainy *et al.* (U.S. 6,153,252). Claims 1-18, 20-75, and 78-88 further stand rejected under 35 U.S.C. §103(a) as being unpatentable over Whitbourne *et al.* (U.S. 6,110,483). Applicants respectfully traverse the rejections.

Claims 1, 10, 20, 32, 56, 63, 75, 78, 79, and 80 are independent.  The remaining claims depend, directly or indirectly, from one of the independent claims.  Thus, remarks that refer to one or more independent claims apply equally to any claim that depends from a referenced independent claim.

The subject matter of each independent claim and the teachings of Sirhan *et al.*, Hossainy *et al.*, and Whitbourne *et al.* are described above in connection with the rejections under 35 U.S.C. §102 and will not be reiterated in this section.

Once again, while the specific disclosures of Sirhan *et al.*, Hossainy *et al.*, and Whitbourne *et al.* (collectively, "the cited documents") differ somewhat, the relevant disclosure for analysis of the rejections is the same: each reference identifies a vast number of individual polymer species.  Consequently, unless otherwise specifically indicated, the remarks that follow apply to each rejection.

Applicants submit that while the cited documents describe classes of polymers that encompass the polymers from which polymers used to form the miscible polymer blends in Applicants' claims may be selected, the cited documents neither teach nor suggest the selection of the recited combinations of polymers.  The cited documents provide no blaze marks that would direct one skilled in the art to select polymers based on their miscibility and/or the recited differences in solubility parameter.

The Examiner suggests that Applicants' claims are obvious in view of the cited documents because each document describes <u>classes</u> of polymers that "[encompass] many of the same polymers and active agents as applicants [sic] currently claimed invention[.]" (Office Action, page 16 with respect to Sirhan *et al.*, page 17 with respect to Hossainy *et al.*, and page 18 with respect to Whitbourne *et al.*) without considering that Applicants' claims are, in fact, directed to a <u>subset</u> of the possible combinations encompassed by the broad disclosures of general classes of polymers in the cited documents.  The subset of polymer combinations to which Applicants' claims are drawn is small and specific in relation to all of the possible

polymer combinations encompassed by the disclosures of the cited documents and is undisclosed in the cited documents. Moreover, the cited documents provide no teaching or suggestion that would direct one skilled in the art to Applicants' claimed subset of polymer combinations from among the innumerable generic polymer combinations described in the cited documents.

Applicants' position is supported by the decision of the Federal Circuit in *In re Baird*, 29 USPQ2d 1550 (1994). In that case, the appealed claim was directed to a flash fusible toner composition comprising a polyester of bisphenol A and an aliphatic carboxylic acid. *Id.* at 1551. The claim was rejected over a prior art reference that described developer compositions comprising a polymeric compound of a generic formula that encompassed the composition of the appealed claim. *Id.* The Board upheld the rejection using reasoning similar to that used to reject Applicants' present claims, "'the fact that [the claimed] binder resin is clearly encompassed by the generic disclosure of [the prior art]...provides ample motivation for the selection of [the claimed composition].'" *Id.*

The Federal Circuit reversed the Board's decision:

> While the [prior art] formula unquestionably encompasses bisphenol A when specific variables are chosen, there is nothing in the disclosure of [the prior art] suggesting that one <u>should</u> select such variables. *Id.* at 1552.

(emphasis added). This reasoning by the Federal Circuit directly applies to the present case. Each of the cited documents encompasses at least some of Applicants' miscible polymer blends when specific variables—e.g., miscibility and/or differences in solubility parameters—are chosen. However, there is nothing in any of the cited documents, either alone or in combination with one another, suggesting that one <u>should</u> select those variables. As a result, the mere generic description of polymer combinations that encompass the claimed miscible polymer blends cannot render Applicants' claims unpatentable in the absence of some suggestion that the specific polymer combinations recited in Applicants' claims should be selected.

After *KSR International Co. v. Teleflex Inc.*, 82 USPQ2d 1385 (U.S. 2007), the rationale used by the Federal Circuit in *In re Baird* was reiterated in *Ortho-McNeil*

*Pharmaceutical, Inc. v. Mylan Laboratories Inc.*, 86 USPQ2d 1196 (Fed. Cir. 2008). The
Federal Circuit reiterated that a claim cannot be rendered obvious by a prior disclosure that
includes several unpredictable alternatives without some guidance to select features recited in the
claim. The Federal Circuit contrasted a situation as presented in *KSR* (e.g., "a situation with a
finite, and in the context of the art, small or easily traversed, number of options" 86 USPQ2d at
1201) with situations in which the path to the claimed subject matter is less direct. The Federal
Circuit rejected the argument, based on language from *KSR*, that claims to a new drug were
obvious in light of "a finite number of identified, predictable solutions." *Id.* The Federal Circuit
noted that one skilled in the art, even if provided with a general class of compound from which to
start, would not necessarily have chosen the starting compound selected by the patentee. *Id.*

        In the present application, the cited documents describe innumerable polymer
species, but provide no guidance to select polymers in relation to one another and based on the
criteria recited in Applicants' claims. Consequently, the obviousness analysis with respect to
Applicants' claims is similar to the analysis by the Federal Circuit in both *In re Baird* and *Ortho-
McNeil*—both cases in which the claimed subject matter was found to be nonobvious—and
distinguishable from the situation in *KSR*.

        Applicants respectfully submit that claims 1-18, 20-75, and 78-88 comply with the
requirements of 35 U.S.C. §103(a) and request that the rejections of claims 1-18, 20-75, and 78-
88 as being unpatentable over Sirhan *et al.*, as being unpatentable over Hossainy *et al.*, and as
being unpatentable over Whitbourne *et al.* be withdrawn.

## Summary

It is respectfully submitted that the pending claims 1-18, 20-75, and 78-88 are in condition for allowance and notification to that effect is respectfully requested. The Examiner is invited to contact Applicants' Representatives at the telephone number listed below if it is believed that prosecution of this application may be assisted thereby.

Respectfully submitted
By
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_3/11/2009_
Date

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CERTIFICATE UNDER 37 CFR §1.8:
The undersigned hereby certifies that the paper(s), as described hereinabove, are being transmitted via the U.S. Patent and Trademark Office electronic filing system in accordance with 37 CFR §1.6(a)(4) to the Patent and Trademark Office addressed to the Mail Stop Amendment, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450, on this _11th_ day of March, 2009.

By: _____
Name: Deb Schurmann

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

| | | | |
|---|---|---|---|
| Appellant(s): SPARER *et al*. | ) | Group Art Unit: 1618 | |
| | ) | | |
| Serial No.: 10/640,853 | ) | Examiner: | James W. Rogers |
| Confirmation No.: 9178 | ) | | |
| | ) | | |
| Filed: August 13, 2003 | ) | | |
| | ) | | |
| For: ACTIVE AGENT DELIVERY SYSTEMS, MEDICAL DEVICES, AND | | | |
| METHODS | | | |

## DECLARATION UNDER 37 C.F.R. §1.132

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

I, Christopher M. Hobot, declare and say as follows:

1.      I am a Senior Research Manager at Medtronic, Inc., 710 Medtronic Parkway, Minneapolis, MN 55432. I own Medtronic common stock and receive stock options as part of my compensation at Medtronic. I received a B.S. in Biomedical Engineering from Johns Hopkins University (Baltimore, MD) in 1985. I joined Medtronic in 1985 in order to apply polymer and drug technologies to the study of medical devices.

2.      I am a co-inventor of the subject matter in the above-identified U.S. Patent Application Serial No. 10/640,853. I have reviewed the Office Action mailed on September 11, 2008, and make this Declaration in support of the patentability of the claims of the above-identified patent application.

3.    Solubility parameters for selected exemplary polymers:

| Polymer | Solubility Parameter $(J^{1/2}/cm^{3/2})$ | Source |
|---|---|---|
| poly(t-butyl methacrylate) | 17.0 | Van Krevelen |
| poly(butyl methacrylate) | 18.1 | Van Krevelen |
| poly(ethyl methacrylate) | 18.5 | Van Krevelen |
| poly(isobutyl methacrylate) | 19.2 | Van Krevelen |
| poly(ethoxyethyl methacrylate) | 19.4 | Van Krevelen |
| poly(benzyl methacrylate) | 20.3 | Van Krevelen |
| poly(methyl methacrylate) | 22.4 | Van Krevelen |
| poly(carbonate urethane), hard segment-dominated | 22.5-24.3 | Calculated |
| poly(carbonate urethane), soft segment-dominated | 18.9 | Calculated |
| poly(ether urethane), hard segment-dominated | 22.5-24.3 | Calculated |
| poly(ether urethane), soft segment-dominated | 17.0-19.6 | Calculated |
| poly(hexyl methylene carbonate) | 18.9 | Calculated |
| poly(bis phenol A carbonate) | 22.9 | Calculated |

4.    ⋅ The solubility parameters provided in Paragraph 3 of this Declaration were obtained as

follows:

- Van Krevelen: D.W. van Krevelen, Properties of Polymers, 3rd ed., Elsevier, 1990.
   Table 7.5. Data were the average if there were two values listed.
- Calculated: Average of the calculated values based on Hoftyzer and van Krevelen's (H-
   vK) method (where the volumes of the chemicals were calculated based on Fedors'
   method) and Hoy's method. See Chapter 7, D.W. van Krevelen, Properties of Polymers,

3rd ed., Elsevier, 1990, for details of all the calculations, where Table 7.8 was for

Hoftyzer and van Krevelen's method, Table 7.3 for Fedors' method, and Table 7.9 and

7.10 for Hoy's method.  An example calculation of a solubility parameter from D.W. van

Krevelen, Properties of Polymers, 3rd ed., Elsevier, 1990, is shown in Appendix A of this

Declaration.

5.      A segmented polymer such as, for example, a polyurethane is composed of multiple

blocks.  A "hard" segment of a polymer is one that is crystalline at use temperature or amorphous

with a glass transition temperature above use temperature (i.e., glassy).  A "soft" segment of a

polymer is one that is amorphous with a glass transition temperature below use temperature (i.e.,

rubbery).  Segmented polymers can have more than one solubility parameter.  The solubility

parameters for a segmented polymer typically refer to the solubility parameters of the hard

and/or soft segment comprising an individual polymer molecule. (Specification, page 11, lines 7-

30).  In the context of the above-identified patent application, a person of ordinary skill in the art

understands that the solubility parameter of the dominant segment in the continuous phase of the

miscible polymer blend is the solubility parameter of a segmented polymer that should be

considered when calculating differences in solubility parameter between the segmented polymer

and either a second polymer or an active agent.

6.      The ranges of solubility parameters for the exemplary hard segment-dominated and soft

segment-dominated polyurethanes are affected by the particular materials in the polyurethane.

Polyurethanes that include alternative materials are possible.  Thus, the solubility parameters of

exemplary polyurethanes provided in Paragraph 3 are not exhaustive and the endpoints of the

provided ranges do not reflect all possible solubility parameters for all of the possible

polyurethanes.  The values provided in Paragraph 3 are merely exemplary.

7.      I further declare that all statements made herein of my own knowledge are true, and that

all statements made on information and belief are believed to be true; and further that these

Declaration Under 37 C.F.R. §1.132
Serial No.: 10/640,853
Confirmation No.: 9178
Filed: August 13, 2003
For: ACTIVE AGENT DELIVERY SYSTEMS, MEDICAL DEVICES, AND METHODS

statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Tile 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent that issues thereon.

Date: 3/11/09

Signed: _Christopher M. Hobot_

Christopher M. Hobot

D.W. VAN KREVELEN

# PROPERTIES OF POLYMERS

THEIR CORRELATION WITH
CHEMICAL STRUCTURE;
THEIR NUMERICAL
ESTIMATION AND PREDICTION
FROM ADDITIVE GROUP
CONTRIBUTIONS

ELSEVIER

THIRD COMPLETELY
REVISED EDITION

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# CONTENTS

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XXII

**Part VII. Comprehensive tables**

# CHAPTER 7

## COHESIVE PROPERTIES AND SOLUBILITY

A quantitative measure of the cohesive properties of a substance is the *cohesive energy*. The cohesive energy per unit of volume is called *cohesive energy density*. The latter is closely related to the *internal pressure*, a quantity appearing in the equation of state.

The square root of cohesive energy density is called *solubility parameter*. It is widely used for correlating polymer solvent interactions. As a refinement, three solubility parameter components can be distinguished, representing dispersion, polar, and hydrogen bond interactions.

Although rigorous additivity rules are not applicable in this case, a fair estimation of the cohesive energy and the solubility parameter of polymers can be made by group contribution methods.

*Introduction*

The cohesive properties of a polymer find direct expression in its solubility in organic liquids. The cohesive properties of a substance are expressed quantitatively in the cohesive energy. This quantity is closely related to the internal pressure, a parameter appearing in the equation of state of the substance.

As early as 1916 Hildebrand pointed out that the order of solubility of a given solute in a series of solvents is determined by the internal pressures of the solvents. Later Scatchard (1931) introduced the concept of "cohesive energy density" into Hildebrands theories, identifying this quantity with the cohesive energy per unit volume. Finally Hildebrand (1936) gave a comprehensive treatment of this concept and proposed the square root of the cohesive energy density as a parameter identifying the behaviour of specific solvents. In 1949 he proposed the term solubility parameter and the symbol $\delta$.

The solubility of a given polymer in various solvents is largely determined by its chemical structure. As a general rule, structural similarity favours solubility. In terms of the above-mentioned quantities this means that the solubility of a given polymer in a given solvent is favoured if the solubility parameters of polymer and solvent are equal. The solubility parameter of the polymer is always defined as the square root of the cohesive energy density in the amorphous state at room temperature. The greater part of this chapter will be devoted to the cohesive energy and the solubility parameter, and to the correlation of these quantities with chemical structure.

Besides the chemical structure, also the physical state of a polymer is important for its solubility properties. Crystalline polymers are relatively insoluble and often dissolve only at temperatures slightly below their crystalline melting points.

As a general rule, the solubility decreases as the molecular mass of the solute increases. This property can be used to fractionate polymers according to molecular mass.

## A. COHESIVE ENERGY

*Definitions*

The cohesive energy $E_{coh}$ of a substance in a condensed state is defined as the increase in internal energy $U$ per mole of substance if all the intermolecular forces are eliminated:

the cohesive energy $= E_{coh} = \Delta U$ \qquad (dimension: J/mol)

Directly related to the cohesive energy are the quantities

cohesive energy density: $e_{coh} = \dfrac{E_{coh}}{V}$ (at 298 K) \qquad (dimension: J/cm$^3$)

solubility parameter $\delta = \left(\dfrac{E_{coh}}{V}\right)^{1/2} = e_{coh}^{1/2}$(at 298 K) \qquad (dimension: J$^{1/2}$/cm$^{3/2}$)

*Determination of $E_{coh}$*

For liquids of low molecular weight, the cohesive energy is closely related to the molar heat of evaporation $\Delta H_{vap}$ (at a given temperature):

$$E_{coh} = \Delta U_{vap} = \Delta H_{vap} - p\Delta V \approx \Delta H_{vap} - RT \qquad (7.1)$$

Therefore, for low-molecular-mass substances $E_{coh}$ can easily be calculated from the heat of evaporation or from the course of the vapour pressure as a function of temperature. As polymers cannot be evaporated, indirect methods have to be used for the determination of their cohesive energy, e.g. comparative swelling or dissolving experiments in liquids of known cohesive energy density. The method is illustrated in fig. 7.1.

*Prediction of the cohesive energy by means of additive functions*

For a prediction of the cohesive energy of substances some group additivity methods have been developed.

For substances of low molecular weight, $E_{coh}$ was considered as an additive property many years ago by Dunkel (1928), who derived group contributions for the cohesive energy of liquids at room temperature. Rheineck and Lin (1968), however, found that for homologous series of low-molecular-weight liquids, the contribution to the cohesive energy of a methylene group was not constant, but depended on the value of other structural groups in the molecule.

Hayes (1961), Di Benedetto (1963), Hoftyzer and Van Krevelen (1970) and Fedors (1974) have applied Dunkel's original method to polymers.

Bunn (1955) dealt with the cohesive energy at the boiling point, while Bondi (1964, 1968) investigated the cohesive energy properties at 0 K ($H_{a}^{o}$).
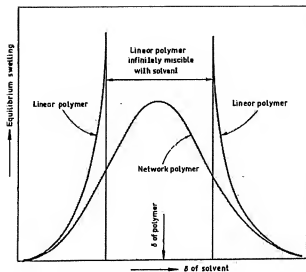
Fig. 7.1. Equilibrium swelling as a function of the solubility parameter of the solvent for linear and cross-linked polystyrene.

Table 7.1 gives a survey of the contributions of the most important structural groups to $E_{coh}$. (Values between brackets are not given as such in the literature but have been calculated by addition and subtraction)[1]

The values given by the different authors show a rough correspondence. Since the cohesive energy will decrease with increasing temperature, the following rule is obeyed in general, as could be expected:

$$H_a^o > E_{coh}(298) > E_{coh}(T_b) .$$

When applied to low-molecular substances, the values of Bunn proved to give by far the best prediction of the cohesive energy. But they can only be applied to substances at the boiling point, so that these values have no direct significance for the cohesive energy of polymers. A good correlation is obtained by the method of Rheineck and Lin, but the disadvantage of their system is that many corrections due to vicinal groups, have to be applied. The systems of Di Benedetto and Hayes have the restriction that only values for a limited number of groups are given by these authors.

Although the work of Rheineck and Lin showed that the additivity principle does not apply exactly to the cohesive energy at room temperature, a reasonably good prediction of

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[1] The values in the literature are normally based on the calorie as unit of energy; here (as a matter of system) the joule is used as unit of energy.

**TABLE 7.1**

Group contributions to $E_{coh}$ (J/mol)

| Group | $H°$ Bondi | $E_{coh}(298)$ Rheineck and Lin | Dunkel | Di Benedetto | Hayes | Fedors | $E_{coh}(T_g)$ Bunn | $E_{coh}(298)$ Hoftyzer and Van Krevelen |
|---|---|---|---|---|---|---|---|---|
| —CH₂— | 10560 | 4150 | 7460 | — | — | 4710 | 7120 | 3640 |
| —CH₃ | 6350 | 5150 | 4150 | 3600 | 4150 | 4940 | 2850 | 4190 |
| H | — | — | — | — | — | — | — | — |
| —Ċ— | (−270) | 4060 | −1590 | — | — | 3430 | (−1840) | 420 |
| —Ċ— | (−8000) | — | — | — | — | — | — | — |
| —CH(CH₃)— | (10290) | (9210) | (−7340) | — | — | 1470 | (−6280) | −5580 |
| —C(CH₃)₂— | (13120) | — | (5870) 7580 | 10390 | 7120 11900 | (8140) (10890) | 5700 7960 | (10050) (13700) |
| H H \C=C/ | — | — | 8300 | 7210 | 7500 | (8620) | 7120 | 10200 |
| —C≡C— | — | — | (2560) 1020 | — | — | (13330) (24240) | (3940) | — |
| H \C=C/ | — | — | 10020 | 10900 | 11480 | (29180) | 10060 | 4860 (14500) |
| —C(CH₃)=CH— | — | — | 30920 | — | — | 31940 | — | — |
| cyclopentyl | 33770 | 25500 | 8630 | — | 23880 | 31940 | 22630 | 31000 |
| cyclohexyl | 38210 | 31220 | 14250 | — | — | 4190 | 16340 (4730) | 25140 |
| phenyl | 41060 | — | — | — | — | 11550 | 11730 | 4470 |
| p-phenylene | 35950 | — | — | — | — | 15490 | 12990 | 12990 |
| —F | — | 11690 | — | — | — | 19050 | 17600 | 15590 |
| —Cl | — | — | — | — | — | 25530 | — | 25000 |
| —Br | — | — | — | — | — | 28960 | — | 25420 |
| —I | — | — | — | — | — | — | — | — |
| —CN | — | — | — | — | 24130 | — | — | — |
| —CH₂CN | — | — | — | — | — | — | — | — |

TABLE 7.1 (continued)

| Group | $H_i^0$ Bondi | $F_{vdw}(298)$ Rheineck and Lin | Dunkel | Di Benedetto | Hayes | Fedors | $F_{vap}(T_b)$ Bunn | $F_{vap}(298)$ Hoftyzer and Van Krevelen |
|---|---|---|---|---|---|---|---|---|
| —OH | — | 32810 | 30380 | — | — | 29800 | 24300 | — |
| —O— | — | — | 6830 | — | 6830 | 3350 | 4190 | 6290 |
| —CO— | — | — | 17890 | — | — | 17370 | 11150 | — |
| —COOH | — | 32810 | 37580 | — | — | 27630 | 23460 | 13410 |
| —COO— | — | (19530) | (16010) | — | 14160 | 18000 | 12150 | — |
| $\overset{O}{\underset{\parallel}{-O-C-O-}}$ | — | — | — | — | — | 17580 | — | — |
| $\overset{O}{\underset{\parallel}{-O-C-O-}}$ H | — | — | — | — | — | 30560 | 16340 | — |
| $\underset{O}{-O-C-O-}$ | — | — | 67880 | — | 44750 | 33490 | 35620 | 60760 |
| $\overset{O}{\underset{\parallel}{-C-N-}}$ H | — | — | — | — | 26310 | 26370 | 36620 | — |
| —O—C—N— | — | — | — | — | — | 14150 | 9220 | 8800 |

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the cohesive energy of polymers can nevertheless be obtained by this method. The values to be used for the group contributions need not be identical, however, with those for low-molecular-weight compounds. Hoftyzer and Van Krevelen (1970) showed that from the available $E_{coh}$-data on polymers a new set of group contribution values could be obtained that gives the best possible correlation with all available data. Updated values are mentioned in table 7.1.

Earlier, Small (1953) had demonstrated that the combination $(E_{coh}V(298))^{1/2} = F$, the *molar attraction constant*, is a useful additive quantity for low-molecular as well as for high-molecular substances. His set of values is very frequently applied. More recently, Hoy (1970) proposed group contributions to $F$, slightly different from those of Small.

Van Krevelen (1965) derived a set of atomic contributions to calculate $F$. Via $F$ it is possible to derive in an indirect way the value of $E_{coh}$ for polymers. The group contributions to $F$, proposed by Small, Hoy and Van Krevelen, are mentioned in table 7.2.

The system of group contributions published by Fedors (1974) gives a less accurate prediction of $E_{coh}$. As Fedors calculated contributions to $E_{coh}$ for a great number of structural groups, however, these data together with Fedors' group contributions to the molecular volume $V$ are reproduced in table 7.3.

Table 7.4 gives the values of $E_{coh}$ for a series of 41 polymers, calculated by different methods, in comparison with the experimental data.

The experimental data of $E_{coh}$ for some polymers show large variations and the predicted values according to each of the methods mentioned in table 7.4 fall within the experimental limits of accuracy. There is some evidence, however, that the lower limits of the experimental values are often more reliable. If this effect is taken into account, the methods of Hayes, Small, Hoy, and Hoftyzer and Van Krevelen are superior to the other methods and each of them predicts the cohesive energy with a mean accuracy of about 10%

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*Example 7.1*

Estimate the cohesive energy of poly(butyl methacrylate).

$$[-CH_2-\underset{\underset{\underset{\underset{\underset{CH_3}{|}}{(CH_2)_3}}{|}}{\overset{\overset{\overset{\overset{CH_3}{|}}{C}}{|}}{\underset{\underset{O}{|}}{\overset{C=O}{|}}}}}{C}-]$$

$M = 142.2$, $\rho_a = 1.045$, $V_a = 136 (cm^3/mol)$
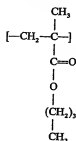
a. with the aid of the group contributions proposed in this chapter (H. and V.Kr.).
b. according to Small's method.

TABLE 7.2
Group contributions to F

| Group | Small | Van Krevelen | Hoy* |
|---|---|---|---|
| —CH$_3$ | 438 | 420 | 303.4 |
| —CH$_2$— | 272 | 280 | 269.0 |
| $\overset{\text{H}}{\underset{\text{ }}{-\text{C}-}}$ | 57 | 140 | 176.0 |
| $-\overset{\text{ }}{\underset{\text{ }}{\text{C}}}-$ | −190 | 0 | 65.5 |
| —CH(CH$_3$)— | 495 | 560 | (479.4) |
| —C(CH$_3$)$_2$— | 686 | 840 | (672.3) |
| $-\overset{\text{H}}{\text{C}}-\overset{\text{H}}{\text{C}}-$ | 454 | 444 | 497.4 |
| $-\overset{\text{H}}{\text{C}}=\text{C}-$ | 266 | 304 | 421.5 |
| —C(CH$_3$)=CH— | (704) | 724 | (724.9) |
| cyclopentyl | – | 1384 | 1295.1 |
| cyclohexyl | – | 1664 | 1473.3 |
| phenyl | 1504 | 1517 | 1398.4 |
| p-phenylene | 1346 | 1377 | 1442.2 |
| —F | (250) | 164 | 84.5 |
| —Cl | 552 | 471 | 419.6 |
| —Br | 696 | 614 | 527.7 |
| —I | 870 | – | – |
| —CN | 839 | 982 | 725.5 |
| —CHCN— | (896) | 1122 | (901.5) |
| —OH | – | 754 | 462.0 |
| —O— | 143 | 256 | 235.3 |
| —CO— | 563 | 685 | 538.1 |
| —COOH | – | 652 | (1000.1) |
| —COO— | 634 | 512 | 668.2 |
| $-\text{O}-\overset{\text{O}}{\underset{\text{ }}{\text{C}}}-\text{O}-$ | – | 767 | (903.5) |
| $-\overset{\text{O}}{\text{C}}-\text{O}-\overset{\text{O}}{\text{C}}-$ | – | 767 | 1160.7 |
| $-\overset{\text{O}}{\text{C}}-\overset{\text{H}}{\text{N}}-$ | – | 1228 | (906.4) |
| $-\text{O}-\overset{\text{O}}{\text{C}}-\overset{\text{H}}{\text{N}}-$ | – | 1483 | (1036.5) |
| —S— | 460 | 460 | 428.4 |

* In the list of Hoy a "base value" has to be added in the summation of increments, viz. 277.0, if the system is used for small molecules, e.g. monomers or solvent molecules (correction for terminal endgroups)

**TABLE 7.3**

Group contributions to $E_{coh}$ and V according to Fedors

| Group | $E_{coh}$ (J/mol) | V (cm³/mol) |
|---|---|---|
| —CH₃ | 4710 | 33.5 |
| —CH₂— | 4940 | 16.1 |
| ⟩CH— | 3430 | −1.0 |
| ⟩C⟨ | 1470 | −19.2 |
| H₂C= | 4310 | 28.5 |
| —CH= | 4310 | 13.5 |
| ⟩C= | 4310 | −5.5 |
| HC≡ | 3850 | 27.4 |
| —C≡ | 7070 | 6.5 |
| Phenyl | 31940 | 71.4 |
| Phenylene (o, m, p) | 31940 | 52.4 |
| Phenyl (trisubstituted) | 31940 | 33.4 |
| Phenyl (tetrasubstituted) | 31940 | 14.4 |
| Phenyl (pentasubstituted) | 31940 | −4.6 |
| Phenyl (hexasubstituted) | 31940 | −23.6 |
| Ring closure 5 or more atoms | 1050 | 16 |
| Ring closure 3 or 4 atoms | 3140 | 18 |
| Conjugation in ring for each double bond | 1670 | −2.2 |
| Halogen attached to carbon atom with double bond | −20% of $E_{coh}$ of halogen | |
| —F | 4190 | 4.0 |
| —F (disubstituted) | 3560 | 18.0 |
| —F (trisubstituted) | 2300 | 20.0 |
| —CF₂— (for perfluoro compounds) | 4270 | 22.0 |
| —CF₃ (for perfluoro compounds) | 4270 | 23.0 |
| —Cl | 11550 | 57.5 |
| —Cl (disubstituted) | 9630 | 24.0 |
| —Cl (trisubstituted) | 7530 | 26.0 |
| —Br | 15490 | 27.3 |
| —Br (disubstituted) | 12350 | 30.0 |
| —Br (trisubstituted) | 10670 | 31.0 |
| —I | 19050 | 32.4 |
| —I (disubstituted) | 16740 | 31.5 |
| —I (trisubstituted) | 16330 | 33.5 |
| —CN | 25530 | 37.0 |
| —OH | 29800 | 24.0 |
| —OH (disubstituted or on adjacent C atoms) | 21850 | 10.0 |
| —O— | 3350 | 13.0 |
| —CHO (aldehyde) | 21350 | 3.8 |
| —CO— | 17370 | 22.3 |
| —COOH | 27630 | 10.8 |
| —CO₂— | 18000 | 28.5 |
| —CO₃— (carbonate) | 17580 | 18.0 |
| —C₂O₃— (anhydride) | 30560 | 22.0 |
| | | 30.0 |

| Group | $E_{coh}$ (J/mol) | V (cm³/mol) | Group | $E_{coh}$ (J/mol) | V (cm³/mol) |
|---|---|---|---|---|---|
| HCOO— (formate) | 18000 | 32.5 | —CH=NOH | 25120 | 24.0 |
| —CO₂CO₂— (oxalate) | 26790 | 37.3 | —NO₂ (aliphatic) | 29300 | 24.0 |
| —HCO₃ | 12560 | 18.0 | —NO₂ (aromatic) | 15360 | 32.0 |
| —COF | 13400 | 29.0 | —NO₃ | 20930 | 33.5 |
| —COCl | 17580 | 38.1 | —NO₂ (nitrite) | 11720 | 33.5 |
| —COBr | 24150 | 41.6 | —NHNO₂ | 39770 | 28.7 |
| —COI | 29300 | 48.7 | —NNO— | 27210 | 10 |
| —NH₂ | 12560 | 19.2 | —SH | 14440 | 28.0 |
| —NH— | 8370 | 4.5 | —S— | 14150 | 12 |
| >N< | 4190 | −9.0 | —S₂— | 23860 | 23.0 |
| —N= | 11720 | 5.0 | —S₃— | 13400 | 47.2 |
| —NHNH₂ | 21980 | − | >SO | 39140 | − |
| >NNH₂ | 16740 | 16 | SO₃ | 18840 | 27.6 |
| >NHNH< | 16740 | 16 | SO₄ | 28460 | 31.6 |
| —N₂ (diazo) | 8370 | 23 | —SO₂Cl | 37070 | 43.5 |
| —N=N— | 4190 | − | —SCN | 20090 | 37.0 |
| >C=N—N=C< | 20090 | 0 | —NCS | 25120 | 40.0 |
| —N=C=N— | 11470 | | P | 9420 | −1.0 |
| —NC | 18840 | 23.1 | PO₂ | 14230 | 22.7 |
| —NF— | 7660 | 33.1 | PO₄ | 20930 | 28.0 |
| —NF₂ | 5070 | 24.5 | PO₄(OH) | 31810 | 32.2 |
| —CONH₂ | 41860 | 17.5 | Si | 3390 | 0 |
| —CONH— | 33490 | 9.5 | SiO₄ | 21770 | 20.0 |
| —CON< | 29510 | −7.7 | B | 13810 | −2.0 |
| HCON< | 27630 | 11.3 | BO₃ | 0 | 20.4 |
| HCONH— | 43950 | 27.0 | | | |
| —NHCOO— | 26370 | 18.5 | Al | 13810 | −2.0 |
| —NHCONH— | 50230 | − | Ga | 13810 | −2.0 |
| —NHCON< | 41860 | | In | 13810 | −2.0 |
| >NCON< | 20930 | −14.5 | Tl | 13810 | −2.0 |
| NH₂COO— | 37000 | − | Ge | 8080 | −1.5 |
| —NCO | 28460 | 35.0 | Sn | 11300 | −1.5 |
| —ONH₂ | 19050 | 20.0 | Pb | 17160 | 2.5 |
| >C=NOH | 25120 | 11.3 | As | 12980 | 7.0 |
| | | | Sb | 16330 | 8.9 |
| | | | Bi | 21350 | 9.5 |
| | | | Se | 17160 | 16.0 |
| | | | Te | 20090 | 17.4 |
| | | | Zn | 14480 | 2.5 |
| | | | Cd | 17790 | 6.5 |
| | | | Hg | 22810 | 7.5 |

TABLE 7.4
Cohesive energy of polymers

| Polymer | $\delta$ ($J^{1/2}/cm^{3/2}$) | | V ($cm^3/mol$) | $E_{coh}$ (from $\delta$) ($J/mol$) | |
|---|---|---|---|---|---|
| | from | to | | from | to |
| Polyethylene | 15.8 | 17.1 | 32.9 | 8200 | 9600 |
| Polypropylene | 16.8 | 18.8 | 49.1 | 13900 | 17400 |
| Polyisobutylene | 16.0 | 16.6 | 66.8 | 17100 | 18400 |
| Polystyrene | 17.4 | 19.0 | 98.0 | 29700 | 35400 |
| Poly(vinyl chloride) | 19.2 | 22.1 | 45.2 | 16700 | 22100 |
| Poly(vinyl bromide) | 19.4 | – | 48.6 | 18300 | – |
| Poly(vinylidene chloride) | 20.3 | 25.0 | 58.0 | 23900 | 36300 |
| Poly(tetrafluoroethylene) | 12.7 | – | 49.5 | 8000 | – |
| Poly(chlorotrifluoroethylene) | 14.7 | 16.2 | 61.8 | 13400 | 16200 |
| Poly(vinyl alcohol) | 25.8 | 29.1 | 35.0 | 23300 | 29600 |
| Poly(vinyl acetate) | 19.1 | 22.6 | 72.2 | 26300 | 36900 |
| Poly(vinyl propionate) | 18.0 | – | 90.2 | 29200 | – |
| Poly(methyl acrylate) | 19.9 | 21.3 | 70.1 | 27800 | 31800 |
| Poly(ethyl acrylate) | 18.8 | 19.2 | 86.6 | 30600 | 31900 |
| Poly(propyl acrylate) | 18.5 | – | 103.1 | 35300 | – |
| Poly(butyl acrylate) | 18.0 | 18.6 | 119.5 | 38700 | 41300 |
| Poly(isobutyl acrylate) | 17.8 | 22.5 | 119.3 | 37800 | 60400 |
| Poly(2,2,3,3,4,4,4-heptafluorobutyl acrylate) | 13.7 | – | 148.0 | 27800 | – |
| Poly(methyl methacrylate) | 18.6 | 26.2 | 86.5 | 29900 | 59400 |
| Poly(ethyl methacrylate) | 18.2 | 18.7 | 102.4 | 33900 | 35800 |
| Poly(butyl methacrylate) | 17.8 | 18.4 | 137.2 | 43500 | 46500 |
| Poly(isobutyl methacrylate) | 16.8 | 21.5 | 135.7 | 38300 | 62700 |
| Poly(tert.-butyl methacrylate) | 17.0 | – | 138.9 | 40100 | – |
| Poly(benzyl methacrylate) | 20.1 | 20.5 | 151.2 | 61100 | 63500 |
| Poly(ethoxyethyl methacrylate) | 18.4 | 20.3 | 145.6 | 49300 | 60000 |
| Polyacrylonitrile | 25.6 | 31.5 | 44.8 | 29400 | 44500 |
| Polymethacrylonitrile | 21.9 | – | 63.9 | 30600 | – |
| Poly($\alpha$-cyanomethyl acrylate) | 28.7 | 29.7 | 82.1 | 67600 | 72400 |
| Polybutadiene | 16.6 | 17.6 | 60.7 | 16700 | 18800 |
| Polyisoprene | 16.2 | 20.5 | 75.7 | 19900 | 31800 |
| Polychloroprene | 16.8 | 18.9 | 71.3 | 20100 | 25500 |
| Polyformaldehyde | 20.9 | 22.5 | 25.0 | 10900 | 12700 |
| Poly(tetramethylene oxide) | 17.0 | 17.5 | 74.3 | 21500 | 22800 |
| Poly(propylene oxide) | 15.4 | 20.3 | 57.6 | 13700 | 23700 |
| Polyepichlorohydrin | 19.2 | – | 69.7 | 25700 | – |
| Poly(ethylene sulphide) | 18.4 | 19.2 | 47.9 | 16200 | 17700 |
| Poly(styrene sulphide) | 19.0 | – | 115.8 | 41800 | – |
| poly(ethylene terephthalate) | 19.9 | 21.9 | 143.2 | 56700 | 68700 |
| Poly(8-aminocaprylic acid) | 26.0 | – | 135.9 | 91900 | – |
| Poly(hexamethylene adipamide) | 27.8 | – | 208.3 | 161000 | – |

Conversion factors: 1 $J^{1/2}/cm^{3/2} = 0.49$ $cal^{1/2}/cm^{3/2}$; 1 $cm^3/mol = 10^{-6}$ $m^3/mol$; 1 $J/mol = 0.24$ cal/mol.

$E_{coh}$ (calculated)
(J/mol)

| Dunkel | Di Benedetto | Hayes | Fedors | Small | Van Krevelen | Hoy | Hoftyzer and Van Krevelen |
|---|---|---|---|---|---|---|---|
| 8300 | 7200 | 8300 | 9880 | 9000 | 9500 | 8800 | 8380 |
| 10020 | – | 11270 | 13080 | 12000 | 14400 | 11400 | 14250 |
| 11730 | 13990 | 16050 | 15830 | 13700 | 18800 | 13300 | 17890 |
| 33480 | 41060 | 34270 | 40310 | 34300 | 38300 | 34700 | 35610 |
| 16810 | 16930 | 21660 | 19920 | 17200 | 17600 | 16500 | 17600 |
| – | – | – | 23860 | 21600 | 22000 | 19500 | 20110 |
| 25310 | – | 15460 | 25670 | 24300 | 25700 | 23800 | 24590 |
| 19840 | – | 9640 | 17180 | 7800 | 8700 | 4400 | 6720 |
| 25460 | – | – | 23250 | 13800 | 15000 | 10500 | 15240 |
| 32940 | – | – | 38170 | – | 39400 | 23500 | – |
| 26030 | 28990 | 25430 | 31080 | 27200 | 25300 | 27800 | 27660 |
| 30180 | 32590 | 25980 | 36020 | 31000 | 29500 | 31500 | 31850 |
| 26030 | 28990 | 25430 | 31080 | 28000 | 26100 | 28600 | 27660 |
| 30180 | 32590 | 25980 | 36020 | 32300 | 30800 | 32800 | 31850 |
| 34330 | 36190 | 33730 | 40960 | 36700 | 35500 | 37000 | 36040 |
| 38480 | 39790 | 37880 | 45900 | 41100 | 40200 | 41400 | 40230 |
| 36050 | – | 36700 | 44160 | 39400 | 40300 | 39300 | 41910 |
| 61110 | – | – | 56860 | 39400 | 37600 | 31800 | 36760 |
| 27740 | – | 30210 | 33830 | 29300 | 30800 | 29900 | 31300 |
| 31890 | – | 34360 | 38770 | 33900 | 35700 | 34500 | 35490 |
| 40190 | – | 42660 | 48650 | 42300 | 44500 | 42600 | 43870 |
| 37760 | – | 41480 | 46910 | 41000 | 45000 | 41000 | 45550 |
| 35320 | – | 42110 | 44720 | 37400 | 44000 | 37500 | 45000 |
| 55350 | – | – | 66000 | 56500 | 59600 | 58200 | 56850 |
| 47020 | – | 49490 | 52000 | 44700 | 51100 | 48300 | 50160 |
| – | – | 28280 | 33900 | 30500 | 43900 | 30600 | 29610 |
| – | – | – | 36650 | 28900 | 44300 | 29100 | 33250 |
| – | – | – | 54650 | 48400 | 58600 | 50300 | 46660 |
| 16600 | 14410 | 15800 | 18500 | 16400 | 16600 | 17700 | 18580 |
| 18320 | 18100 | 19780 | 23210 | 20600 | 21800 | 21100 | 22880 |
| 25110 | 20950 | 20910 | 30050 | 26600 | 25000 | 26700 | 26230 |
| 10980 | – | 10980 | 8290 | 6900 | 11500 | 10200 | 10480 |
| 23430 | – | 23430 | 23110 | 20400 | 25500 | 23100 | 23050 |
| 16850 | – | 18110 | 16430 | 14400 | 20900 | 16800 | 20540 |
| 27790 | – | – | 28210 | 24100 | 29200 | 26900 | 28080 |
| – | – | – | 24030 | 21000 | 21700 | 19500 | 17180 |
| – | – | – | 54460 | 45400 | 49600 | 44600 | 44410 |
| – | – | 60500 | 77820 | 69600 | 61200 | 76800 | 60340 |
| 96930 | – | 73800 | 68070 | – | 74800 | 57100 | 90090 |
| 177260 | – | 131000 | 116380 | – | 132600 | 97300 | 163420 |

*Solution*
    Addition of group contributions to be found in tables 7.1 and 7.2 gives the following result:

| groups | $\Sigma E_i$ | $\Sigma F_i$ |
|---|---|---|
| 4 $CH_2$— | 16760 | 1088 |
| 2 —$CH_3$ | 19280 | 876 |
| 1 $\diagdown C \diagup$ | −5580 | −190 |
| 1 —$COO$— | 13410 | 634 |
| | $E_{coh} = 43870$ | $F = 2408$ |

a. the direct method gives $E_{coh} = 43870$ J/mol unit,
b. Small's method leads to:

$$E_{coh} = \frac{F^2}{V} = 42700 \text{ J/mol.}$$

Experimental values of the solubility parameter $\delta$ range from 17.8 to 18.4. This corresponds to values of $E_{coh} = \delta^2 V$ from 43500 to 46500 J/mol.

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    The cohesive energy is an important quantity for characterizing the physical state of a given polymer. It is related to other polymer properties for which cohesive forces are important, as will be discussed in other chapters.
    The cohesive energy has found its most important applications, however, in the interactions between polymers and solvents. For this purpose the solubility parameter $\delta$ is generally used. Therefore the greater part of this chapter will be devoted to properties and applications of the solubility parameter.

## B. SOLUBILITY

*The solubility parameter*
    At first sight it is rather unpractical to use a quantity $\delta$ with dimensions $J^{1/2}/cm^{3/2}$ instead of the cohesive energy. The definition of $\delta$ is based, however, on thermodynamic considerations, as will be discussed below. In the course of time the values of $\delta$, expressed in $cal^{1/2}/cm^{3/2}$, have become familiar quantities for many investigators. In this connection the change to SI units has some disadvantages. Conversion of $cal^{1/2}/cm^{3/2}$ into $J^{1/2}/cm^{3/2}$ is simple, however, as it only requires multiplication by a factor of 2 (2.046 to be exact).
    The thermodynamic criteria of solubility are based on the free energy of mixing $\Delta G_M$. Two substances are mutually soluble if $\Delta G_M$ is negative. By definition,

$$\Delta G_M = \Delta H_M - T \Delta S_M \qquad (7.2)$$

where
$\Delta H_M$ = enthalpy of mixing
$\Delta S_M$ = entropy of mixing.
As $\Delta S_M$ is generally positive, there is a certain limiting positive value of $\Delta H_M$ below which dissolution is possible.

As early as 1916 Hildebrand tried to correlate solubility with the cohesive properties of the solvents. In 1949 he proposed the term solubility parameter and the symbol $\delta$, as defined in the beginning of this chapter.

According to Hildebrand, the enthalpy of mixing can be calculated by

$$\Delta h_M = \phi_1 \phi_2 (\delta_1 - \delta_2)^2 \tag{7.3}$$

where
$\Delta h_M$ = enthalpy of mixing per unit volume
$\phi_1$ and $\phi_2$ = volume fractions of components 1 and 2
$\delta_1$ and $\delta_2$ = solubility parameters of components 1 and 2.

Eq. (7.3) predicts that $\Delta H_M = 0$ if $\delta_1 = \delta_2$, so that two substances with equal solubility parameters should be mutually soluble due to the negative entropy factor. This is in accordance with the general rule that chemical and structural similarity favours solubility. As the difference between $\delta_1$ and $\delta_2$ increases, the tendency towards dissolution decreases.

We may conclude that as a requirement for the solubility of a polymer P in a solvent S, the quantity

$$(\delta_P - \delta_S)^2$$

has to be small, as small as possible[1].

The solubility parameter of a given material can be calculated either from the cohesive energy, or from the molar attraction constant F, as $\delta = F/V$.

In the derivation of eq. (7.3) it was assumed that no specific forces are active between the structural units of the substances involved. Therefore it does not hold for crystalline polymers.

Also if one of the substances involved contains strongly polar groups or hydrogen bridges, $\Delta H_M$ may become higher than predicted by eq. (7.3), so that $\Delta G_M$ becomes positive even for $\delta_1 = \delta_2$ and dissolution does not occur. Conversely, if both substances contain polar groups or hydrogen bridges, solubility may be promoted.

For these reasons a more refined treatment of the solubility parameter concept is often necessary, especially for interactions between polymers and solvents. Nevertheless, the solubility parameters of polymers and solvents are important quantities in all phenomena involving interactions between polymers and solvents.

Table 7.5 gives $\delta$-values for some polymers (experimental and calculated) and Table VI, Part VII, gives solubility parameter values for a number of solvents.

Evidently, the most important application of the solubility parameters to be discussed in this chapter is the prediction of the solubility of polymers in various solvents. A first requirement of mutual solubility is that the solubility parameter of the polymer $\delta_P$ and that of the solvent $\delta_S$ do not differ too much.

This requirement, however, is not sufficient. There are combinations of polymer and

---

[1] This quantity plays a part in an expression for the thermodynamic interaction parameter $\chi$:

$$\chi \approx 0.34 + \frac{V_s}{RT} (\delta_P - \delta_S)^2.$$

TABLE 7.5

Experimental and calculated values of δ for some polymers

| Polymer | δ exp. $(J^{1/2}/cm^{3/2})$ | | δ calc. (H. + v.K.) $(J^{1/2}/cm^{3/2})$ |
|---|---|---|---|
| | from | to | |
| Polyethylene | 15.8 | 17.1 | 16.0 |
| Polypropylene | 16.8 | 18.8 | 17.0 |
| Polyisobutylene | 16.0 | 16.6 | 16.4 |
| Polystyrene | 17.4 | 19.0 | 19.1 |
| Poly(vinyl chloride) | 19.2 | 22.1 | 19.7 |
| Poly(vinyl bromide) | 19.4 | – | 20.3 |
| Poly(vinylidene chloride) | 20.3 | 25.0 | 20.6 |
| Poly(tetrafluoroethylene) | 12.7 | – | 11.7 |
| Poly(chlorotrifluoroethylene) | 14.7 | 16.2 | 15.7 |
| Poly(vinyl alcohol) | 25.8 | 29.1 | – |
| Poly(vinyl acetate) | 19.1 | 22.6 | 19.6 |
| Poly(vinyl propionate) | 18.0 | – | 18.8 |
| Poly(methyl acrylate) | 19.9 | 21.3 | 19.9 |
| Poly(ethyl acrylate) | 18.8 | 19.2 | 19.2 |
| Poly(propyl acrylate) | 18.5 | – | 18.7 |
| Poly(butyl acrylate) | 18.0 | 18.6 | 18.3 |
| Poly(isobutyl acrylate) | 17.8 | 22.5 | 18.7 |
| Poly(2,2,3,3,4,4,4-heptafluorobutyl acrylate) | 13.7 | – | 15.8 |
| Poly(methyl methacrylate) | 18.6 | 26.2 | 19.0 |
| Poly(ethyl methacrylate) | 18.2 | 18.7 | 18.6 |
| Poly(butyl methacrylate) | 17.8 | 18.4 | 17.9 |
| Poly(isobutyl methacrylate) | 16.8 | 21.5 | 18.3 |
| Poly(tert.-butyl methacrylate) | 17.0 | – | 18.0 |
| Poly(benzyl methacrylate) | 20.1 | 20.5 | 19.3 |
| Poly(ethoxyethyl methacrylate) | 18.4 | 20.3 | 18.6 |
| Polyacrylonitrile | 25.6 | 31.5 | 25.7 |
| Polymethacrylonitrile | 21.9 | – | 22.8 |
| Poly(α-cyanomethyl acrylate) | 28.7 | 29.7 | 23.8 |
| Polybutadiene | 16.2 | 17.6 | 17.5 |
| Polyisoprene | 16.6 | 20.5 | 17.4 |
| Polychloroprene | 16.8 | 18.9 | 19.2 |
| Polyformaldehyde | 20.9 | 22.5 | 20.5 |
| Poly(tetramethylene oxide) | 17.0 | 17.5 | 17.6 |
| Poly(propylene oxide) | 15.4 | 20.3 | 18.9 |
| Polyepichlorohydrin | 19.2 | – | 20.1 |
| Poly(ethylene sulphide) | 18.4 | 19.2 | 18.9 |
| Poly(styrene sulphide) | 19.0 | – | 19.6 |
| Poly(ethylene terephthalate) | 19.9 | 21.9 | 20.5 |
| Poly(8-aminocaprylic acid) | 26.0 | – | 25.7 |
| Poly(hexamethylene adipamide) | 27.8 | – | 28.0 |

solvent for which $\delta_p \approx \delta_s$, but yet do not show mutual solubility. Mutual solubility only occurs if the degree of hydrogen bonding is about equal. This led Burrell (1955) towards a division of solvents into three classes, viz. poorly, moderately and strongly hydrogen bonded. In combination with the total solubility parameter δ a considerably improved classification of solvents is obtained. The system of Burrell is represented in table 7.6.

**TABLE 7.6**
Hydrogen-bonding tendency of solvents

| Poorly Hydrogen-Bonded | Moderately Hydrogen-Bonded | Strongly Hydrogen-Bonded |
|---|---|---|
| | | ethylene glycol |
| | ethylene carbonate | |
| | | methanol |
| | butyrolactone | |
| | | |
| | propylene carbonate | |
| | | ethanol |
| nitromethane | | formic acid |
| | DMF | n-propanol |
| | acetonitrile | isopropanol |
| | HMPT | |
| | NMP | m-cresol |
| | DMA | |
| nitroethane | TMU | |
| | | |
| | dioxene | |
| | acetone | |
| tetrachloroethane | tetrahydrofuran | |
| chlorobenzene | cyclohexanone | |
| Tetralin | methyl acetate | |
| chloroform | methyl ethyl ketone | |
| benzene | ethyl acetate | |
| toluene | | |
| p-xylene | | |
| carbon tetrachloride | butyl acetate | |
| n-butyl chloride | | |
| cyclohexane | | |
| | | |
| heptene | diethyl ether | |

δ scale: 30, 28, 26, 24, 22, 20, 18, 16

DMA  -  dimethylacetamide
DMF  -  dimethylformamide
HMPT -  hexamethylphosphoramide
NMP  -  N-methylpyrrolidone
TMU  -  tetramethylurea

*Refinements of the solubility parameter concept*

In the derivation of eq. (7.3) by Hildebrand only dispersion forces between structural units have been taken into account. For many liquids and amorphous polymers, however, the cohesive energy is also dependent on the interaction between polar groups and on hydrogen bonding. In these cases the solubility parameter as defined corresponds with the total cohesive energy.

Formally, the cohesive energy may be divided into three parts, corresponding with the three types of interaction forces

$$E_{coh} = E_d + E_p + E_h \qquad (7.4)$$

where

$E_d$ = contribution of dispersion forces
$E_p$ = contribution of polar forces
$E_h$ = contribution of hydrogen bonding

The corresponding equation for the solubility parameter is

$$\delta^2 = \delta_d^2 + \delta_p^2 + \delta_h^2 \qquad (7.5)$$

The equivalent of eq. (7.3) becomes

$$\Delta h_M = \phi_1 \phi_2 [(\delta_{d1} - \delta_{d2})^2 + (\delta_{p1} - \delta_{p2})^2 + (\delta_{h1} - \delta_{h2})^2] \qquad (7.6)$$

Unfortunately, values of $\delta_d$, $\delta_p$ and $\delta_h$ cannot be determined directly.

There are, in principle, two ways for a more intricate use of the solubility parameter concept:
a. the use of other measurable physical quantities besides the solubility parameter for expressing the solvent properties of a liquid;
b. indirect determination of the solubility parameter components $\delta_d$, $\delta_p$ and $\delta_h$.

The first method was used by Beerbower et al. (1967), who expressed the amount of hydrogen bonding energy by the *hydrogen bonding number* $\Delta \nu$. This quantity was defined by Gordy and Stanford (1939–1941) as the shift of the infrared absorption band in the 4 $\mu$m range occurring when a given liquid is added to a solution of deuterated methanol in benzene.

Beerbower et al. plotted the data for various solvents in a diagram with the solubility parameter $\delta$ along the horizontal axis and the hydrogen bonding number $\Delta \nu$ along the vertical axis. All the solvents in which a given polymer is soluble fall within a certain region. As an example, fig. 7.2 shows such a diagram for polystyrene.

Crowley et al. (1966, 1967) used an extension of this method by including the dipole moment of the solvent in the characterization. However, as this involves a comparison of a number of solvents in a three-dimensional system, the method is impractical.

The second method was developed by Hansen (1967, 1969). Hansen presumed the applicability of eqs. (7.5) and (7.6) and developed a method for the determination of $\delta_d$, $\delta_p$ and $\delta_h$ for a number of solvents. The value of $\delta_d$ of a given solvent was assumed to be equal to that of a non-polar substance (e.g. hydrocarbon) of about the same chemical structure. This permitted the calculation of $\delta_p^2 + \delta_h^2 = \delta^2 - \delta_d^2 (= \delta_a^2)$.
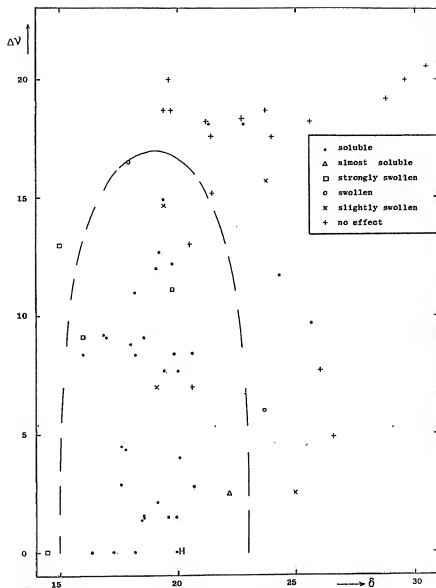
Fig. 7.2. Solubility of polystyrene in various solvents in the Δν − δ diagram.

Now Hansen determined experimentally the solubility of a number of polymers in a series of solvents. All the solvents were characterized by a point in a three-dimensional structure, in which $\delta_d$, $\delta_p$ and $\delta_h$ could be plotted on three mutually perpendicular axes. The values of $\delta_p$ and $\delta_h$ for the various solvents were shifted until all the solvents in which a given polymer was soluble were close together in space.

Values of $\delta_d$, $\delta_p$ and $\delta_h$ for a number of solvents determined in this way can be found in table VI (Part VII). For comparison also values of the dipole moment $\mu$ and the hydrogen bonding number $\Delta\nu$ are mentioned.

Hansen also determined $\delta_d$, $\delta_p$ and $\delta_h$ of the polymers involved, being the coordinates of the center of the solvents region in his three-dimensional structure. Table 7.7 shows his parameters for some polymers[1].

The method of Hansen has the disadvantage that three-dimensional structures are necessary for a graphical representation of the interaction between polymers and solvents. For practical applications a two-dimensional method is to be preferred.

Thermodynamic considerations led Bagley et al. (1971) to the conclusion that the effects of $\delta_d$ and $\delta_p$ show close similarity, while the effect of $\delta_h$ is of a quite different nature. Accordingly, they introduced the parameter $\delta_v = \sqrt{(\delta_d^2 + \delta_p^2)}$. This leads to a diagram in which $\delta_v$ and $\delta_h$ are plotted on the axes.

Such a diagram is shown in fig. 7.3 for the interaction between polystyrene and a number of solvents. The majority of the points for good solvents indeed fall in a single region of fig. 7.3. This region can approximately be delimitated by a circle the centre of which is indicated by the symbol*. (This location differs from that proposed by Hansen, according to the data of table 7.7, and indicated by the symbol H.) Obviously, fig. 7.3 is superior to fig. 7.2 in demarcating a solubility region.

A method of representation very similar to that of fig. 7.3 was proposed by Chen (1971). He introduced a quantity

$$\chi_{11} \approx \frac{V_s}{RT} \left[ (\delta_{dS} - \delta_{dP})^2 + (\delta_{pS} - \delta_{pP})^2 \right] \tag{7.7}$$

TABLE 7.7
Hansen's specified solubility parameters for some polymers

| Polymer | $\delta$ | $\delta_d$ | $\delta_p$ | $\delta_h$ |
|---|---|---|---|---|
| Polyisobutylene | 17.6 | 16.0 | 2.0 | 7.2 |
| Polystyrene | 20.1 | 17.6 | 6.1 | 4.1 |
| Poly(vinyl chloride) | 22.5 | 19.2 | 9.2 | 7.2 |
| Poly(vinyl acetate) | 23.1 | 19.0 | 10.2 | 8.2 |
| Poly(methyl methacrylate) | 23.1 | 18.8 | 10.2 | 8.6 |
| Poly(ethyl methacrylate) | 22.1 | 18.8 | 10.8 | 4.3 |
| Polybutadiene | 18.8 | 18.0 | 5.1 | 2.5 |
| Polyisoprene | 18.0 | 17.4 | 3.1 | 3.1 |

[1] A number of these values, however, seem to be rather doubtful (see, e.g., the $\delta_h$ values of polyisobutylene and polystyrene and the $\delta_p$ value of polybutadiene). Koenhen and Smolders (1975) made a critical evaluation of this and similar methods.

where the subscripts S and P denote solvent and polymer, respectively. The solubility data are then plotted in a $\delta_h - \chi_H$-diagram. A disadvantage of this method is that the characteristics of the polymer should be estimated beforehand.

Other two-dimensional methods for the representation of solubility data are the
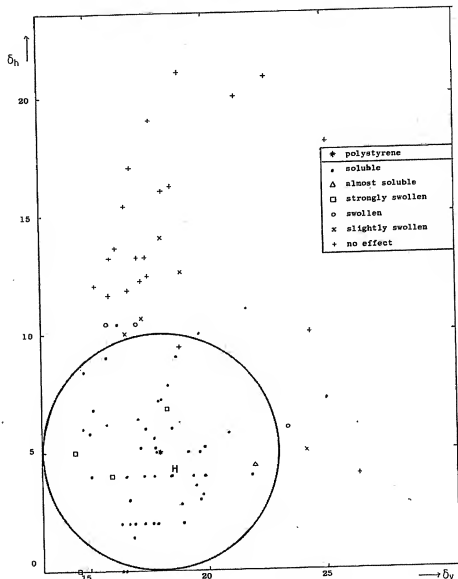


Fig. 7,3. Solubility of polystyrene in various solvents in the $\delta_v - \delta_h$ diagram.

$\delta_p - \delta_h$-diagram proposed by Henry (1974), the $\delta - \delta_h$-diagram proposed by Hoernschemeyer (1974) or the $\delta - \delta_a$ diagram*.

At the moment the $\delta_v - \delta_h$-diagram seems to be the most efficient way to represent polymer–solvent interactions.

*Solubility of polymers in solvents*

In the $\delta_h - \delta_v$-diagram the degree of solubility (volume of polymer per volume of solvent) can be indicated by a number. This is shown in fig. 7.4 for the data of Kambour et al. (1973) on the solubility of polystyrene in a number of solvents.

The solubility region can approximately be delimitated by a circle with a radius of about 5 $\delta$-units. The center of this circle is indicated by the symbol*; it has the coordinate values: $\delta_v = 18$; $\delta_h = 5$. It can be seen that the solubility increases approximately as the distance from the centre decreases.

As a general rule, polystyrene is soluble in solvents for which

$$\left| \sqrt{(\delta_v - 18)^2 + (\delta_h - 5)^2} \right| < 5 \tag{7.8}$$

The literature mentions analogous data for a number of other polymers, which will not be discussed here. When plotted in a $\delta_h - \delta_v$-diagram, they generally show the same type of picture. The reader should be warned, however, of the limited accuracy of this method. The diagrams give only an indication of solubility relationships and always show a number of deviating points.

*Solubility limits and Flory-temperature*

The solubility limits of a given polymer are closely related to the Flory-temperatures of the polymer in various solvents.

The *Flory-temperature* ($\Theta_F$) is defined as the temperature where the *partial molar free energy* due to polymer-solvent interactions *is zero*, so that the polymer-solvent systems show ideal solution behaviour. If $T = \Theta_F$ the molecules can interpenetrate one another freely with no net interactions. At $T < \Theta_F$ the molecules attract one another. If the temperature is much below $\Theta_F$, precipitation occurs.

Thermodynamical considerations have led to the following equation for the temperature at which phase separation of polymer solutions begins:

$$T_{cr} \approx \frac{\Theta_F}{1 + \dfrac{C}{M^{1/2}}} \qquad \text{where C is a constant for the polymer-solvent system.} \tag{7.9}$$

---

* The different combinations are all derived from the basic scheme:

$$\boxed{\delta^2 = \underbrace{\overbrace{\delta_d^2 + \delta_p^2}^{\delta_v^2} + \delta_h^2}_{\delta_a^2}} \tag{7.5a}$$

It is clear that the *Flory-temperature is the critical miscibility temperature in the limit of infinite molecular weight.*

Fox (1962) succeeded in correlating $\Theta_F$-temperatures of polymer–solvent systems with the solubility parameter $\delta_s$ of the solvent. Plots of $\delta_s$ as a function of $\Theta_F$ are shown in fig. 7.5.
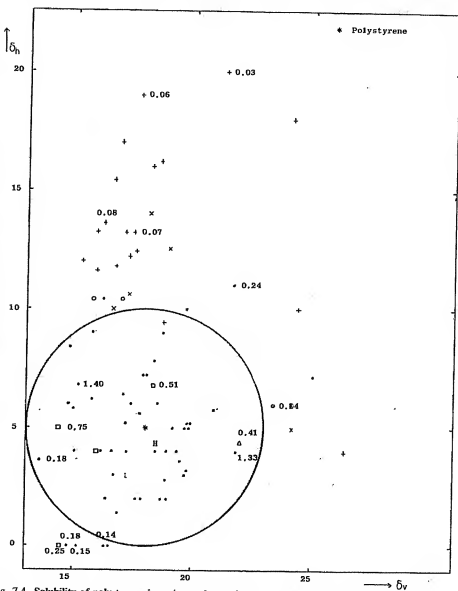


Fig. 7.4. Solubility of polystyrene in various solvents (numbers: vol. styrene/vol. solvent).
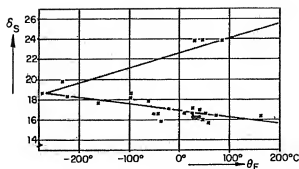
a) poly (methyl methacrylate).
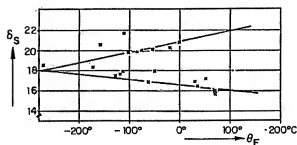


b) polystyrene
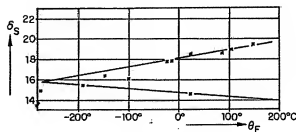


c) polyisobutylene

Fig. 7.5. Solubility parameters and Θ-temperatures (Van Krevelen and Hoftyzer, 1967).

At a given temperature, a solvent for the polymer should have a δ-value approximately between the limits, indicated by the two straight lines in the figure.

An even better correlation of Flory-temperatures with solubility parameters can be given in a $\delta_h - \delta_v$-diagram. This is shown in fig. 7.6 for polystyrene. The circle drawn in fig. 7.6 corresponds again with eq. (7.8).
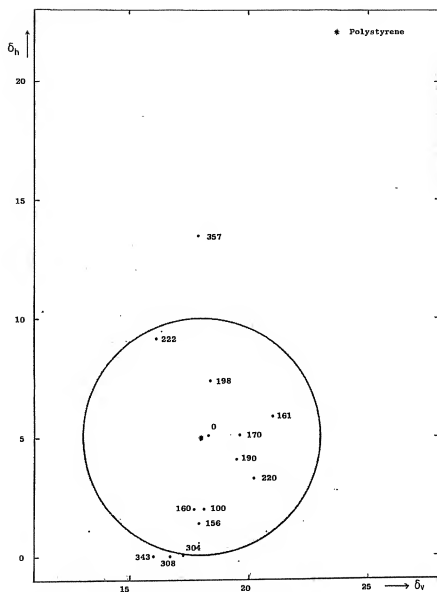
Fig. 7.6. Flory-temperatures of polystyrene in various solvents.

*Prediction of solubility-parameter components*

The solubility parameter components $\delta_d$, $\delta_p$ and $\delta_h$ (and their combinations $\delta_v = \sqrt{\delta_p^2 + \delta_h^2}$ and $\delta_v = \sqrt{\delta_d^2 + \delta_p^2}$) are known for a limited number of solvents only. Therefore a method for predicting these quantities is valuable.

It is to be expected that the polar component $\delta_p$ is correlated with the dipole moment $\mu$

and that the hydrogen bonding component $\delta_h$ is correlated with the hydrogen bonding number $\Delta \nu$. This is not of much use, however, as also $\mu$ and $\Delta \nu$ are only known for a limited number of solvents. A useful prediction method must be based on the molecular structure of the solvent.

The available experimental data prove, however, that it is impossible to derive a simple system for an accurate prediction of solubility parameter components from the chemical structure. Especially the interaction of different structural groups in producing overall polar and hydrogen-bonding properties is so complicated that it does not obey simple rules.

If nevertheless such a prediction method is presented here, it does not pretend to give more than rather rough estimates. Yet this may sometimes be preferable to a complete lack of data.

Two approaches have been published, viz. that of Hoftyzer and Van Krevelen (1976) and that of Hoy (1985); in both methods the same basic assumption is made, that of Hansen:

$$E_{coh} = E_d + E_p + E_h \text{ (see eq. 7.4), so:}$$

$$\delta_t^2 = \delta_d^2 + \delta_p^2 + \delta_h^2 \text{ (see eq. 7.5)}$$

1) *Method of Hoftyzer and Van Krevelen (1976)*

The solubility parameter components may be predicted from group contributions, using the following equations:

$$\delta_d = \frac{\sum F_{di}}{V} \tag{7.10}$$

$$\delta_p = \frac{\sqrt{\sum F_{pi}^2}}{V} \tag{7.11}$$

$$\delta_h = \sqrt{\frac{\sum E_{hi}}{V}} \tag{7.12}$$

This means that for the prediction of $\delta_d$ the same type of formula is used as Small proposed for the prediction of the total solubility parameter $\delta$. The group contributions $F_{di}$ to the dispersion component $F_d$ of the molar attraction constant can simply be added.

The same method holds for $\delta_p$ as long as only one polar group is present. To correct for the interaction of polar groups, the form of equation (7.11) has been chosen.

The polar component is still further reduced, if two identical polar groups are present in a symmetrical position. To take this effect into account, the value of $\delta_p$, calculated with eq. (7.11) must be multiplied by a symmetry factor of:

0.5 for one plane of symmetry
0.25 for two planes of symmetry
0 for more planes of symmetry

The F-method is not applicable to the calculation of $\delta_h$. It has already been stated by Hansen that the hydrogen bonding energy $E_{hi}$ per structural group is approximately

constant. This leads to the form of equation (7.12). For molecules with several planes of symmetry, $\delta_h = 0$.

The group contributions $F_{di}$, $F_{pi}$ and $E_{hi}$ for a number of structural groups are given in table 7.8.

TABLE 7.8.
Solubility parameter component group contributions (method Hoftyzer-Van Krevelen)

| Structural group | $F_{di}$ (J$^{1/2}$ · cm$^{3/2}$ · mol$^{-1}$) | $F_{pi}$ (J$^{1/2}$ · cm$^{3/2}$ · mol$^{-1}$) | $E_{hi}$ (J/mol) |
|---|---|---|---|
| —CH₃ | 420 | 0 | 0 |
| —CH₂— | 270 | 0 | 0 |
| —CH— | 80 | 0 | 0 |
| —C— | −70 | 0 | 0 |
| =CH₂ | 400 | 0 | 0 |
| =CH— | 200 | 0 | 0 |
| =C< | 70 | 0 | 0 |
| (benzene ring) | 1620 | 0 | 0 |
| (cyclohexane ring) | 1430 | 110 | 0 |
| (substituted ring) (o, m, p) | 1270 | 110 | 0 |
| —F | (220) | – | – |
| —Cl | 450 | 550 | 400 |
| —Br | (550) | – | – |
| —CN | 430 | 1100 | 2500 |
| —OH | 210 | 500 | 20000 |
| —O— | 100 | 400 | 3000 |
| —COH | 470 | 800 | 4500 |
| —CO— | 290 | 770 | 2000 |
| —COOH | 530 | 420 | 10000 |
| —COO— | 390 | 490 | 7000 |
| HCOO— | 530 | – | – |
| —NH₂ | 280 | – | 8400 |
| —NH— | 160 | 210 | 3100 |
| —N< | 20 | 800 | 5000 |
| —NO₂ | 500 | 1070 | 1500 |
| —S— | 440 | – | – |
| —PO₄ | 740 | 1890 | 13000 |
| ring | 190 | – | – |
| one plane of symmetry | – | 0.50× | – |
| two planes of symmetry | – | 0.25× | – |
| more planes of symmetry | – | 0× | 0× |

*Example 7.2*
Estimate the solubility parameter components of diacetone alcohol

$$H_3C-\underset{\underset{O}{\|}}{C}-CH_2-\underset{\underset{CH_3}{|}}{\overset{\overset{OH}{|}}{C}}-CH_3$$
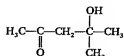
*Solution*
The molar volume $V = 123.8$ cm$^3$/mol. Addition of the group contributions gives

| | $F_{di}$ | $F_{pi}^2$ | $E_{hi}$ |
|---|---|---|---|
| 3 —CH$_3$ | 1260 | 0 | 0 |
| —CH$_2$— | 270 | 0 | 0 |
| $\diagdown C \diagup$ | ~70 | 0 | 0 |
| —CO— | 290 | 593000 | 2000 |
| —OH | 210 | 250000 | 20000 |
| | 1960 | 843000 | 22000 |

According to equations (7.10) to (7.12)

$$\delta_d = \frac{\sum F_{di}}{V} = \frac{1960}{123.8} = 15.8 \text{ J}^{1/2}/\text{cm}^{3/2}$$

$$\delta_p = \frac{\sqrt{\sum F_{pi}^2}}{V} = \frac{\sqrt{843000}}{123.8} = 7.4 \text{ J}^{1/2}/\text{cm}^{3/2}$$

$$\delta_h = \sqrt{\frac{\sum E_{hi}}{V}} = \sqrt{\frac{22000}{123.8}} = 13.3 \text{ J}^{1/2}/\text{cm}^{3/2}$$

The literature values are $\delta_d = 15.7$
$\delta_p = 8.2$
$\delta_h = 10.9$

From the calculated components an overall value of the solubility parameter is found:

$$\delta = \sqrt{\delta_d^2 + \delta_p^2 + \delta_h^2} = 21.9 \text{ J}^{1/2}/\text{cm}^{3/2}$$

The experimental values for $\delta$ vary from 18.8 to 20.8 J$^{1/2}$/cm$^{3/2}$.

2) *Method of Hoy (1985, 1989)*

Hoy's method is in many respects different from that of Hoftyzer and Van Krevelen. Table 7.9 gives a survey of the system of equations to be used. It contains four additive molar functions, a number of auxiliary equations and the final expressions for $\delta_{t(total)}$ and for the components of $\delta$.

$F_t$ is the molar attraction function, $F_p$ its polar component (both as discussed earlier); V is the molar volume of the solvent molecule or the structural unit of the polymer. $\Delta_T$ is the Lyderson correction for non-ideality, used in the auxiliary equations. The values for

TABLE 7.9
The equations to be used in Hoy's system (1985) for estimation of the solubility parameter and its components. See text for significance of symbols.

| Formulae | Low-molecular liquids (Solvents) | Amorphous Polymers |
|---|---|---|
| Additive molar functions | $F_t = \Sigma N F_t$ <br> $F_p = \Sigma N F_{p,i}$ <br> $V = \Sigma N V_i$ <br> $\Delta_T = \Sigma N \Delta_{T,i}$ | $F_t = \Sigma N_i F_{t,i}$ <br> $F_p = \Sigma N_i F_{p,i}$ <br> $V = \Sigma N_i V_i$ <br> $\Delta_T^{(p)} = \Sigma N_i \Delta_T^{(p)}$ |
| Auxiliary equations | $\text{Log } \bar{a} = 3.39\left(\dfrac{T_b}{T_c}\right) - 0.1585 - \log V$ <br><br> $T_b = \text{boiling point}; T_c = \text{critical temp.}$ <br><br> $\left(\dfrac{T_b}{T_c}\right) = 0.567 + \Delta_T - (\Delta_T)^2$ <br><br> (Lyderson equation) | $\bar{a}^{(p)} = \dfrac{777\Delta_T^{(p)}}{V}$ <br><br><br> $\bar{n} = \dfrac{0.5}{\Delta_T^{(p)}}$ |
| Expressions for $\delta$ and $\delta$-components <br><br> (Note that $F_t$ must always be combined with a base value: B for liquids and $B/\bar{n}$ for polymers) | $\delta_t = \dfrac{F_t + B}{V} \qquad B = 277$ <br><br> $\delta_p = \delta_t \left(\dfrac{1}{\bar{a}}\dfrac{F_p}{F_t + B}\right)^{1/2}$ <br><br> $\delta_h = \delta_t \left(\dfrac{\bar{a}-1}{\bar{a}}\right)^{1/2}$ <br><br> $\delta_d = (\delta_t^2 - \delta_p^2 - \delta_h^2)^{1/2}$ | $\delta_t = \dfrac{F_t + B/\bar{n}}{V}$ <br><br> $\delta_p = \delta_t \left(\dfrac{1}{\bar{a}^{(p)}}\dfrac{F_p}{F_t + B/\bar{n}}\right)^{1/2}$ <br><br> $\delta_h = \delta_t \left(\dfrac{\bar{a}^{(p)}-1}{\bar{a}^{(p)}}\right)^{1/2}$ <br><br> $\delta_d = (\delta_t^2 - \delta_p^2 - \delta_h^2)^{1/2}$ |

low-molecular liquids were derived by Lydersen (1955); the corresponding values for polymers, which are slightly different, have been derived by Hoy ($\Delta_T^{(p)}$).

Of the other quantities in the auxiliary equations, the significance is the following: $\bar{a}$ is the *molecular aggregation number*, describing the association of the molecules; $\bar{n}$ is the number of repeating units per effective chain segment of the polymer.

It must be emphasized that Hoy is the only author who uses a "base value" in the calculation of $F_t$, whereas he neglects a base value in $V$; it was mentioned earlier that Traube (1895) already proved that for the additive calculation of the molar volume of liquids a base value has to be used (see Ch. 4).

Hoy's method will now be illustrated by two numerical examples.

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*Example 7.3*

Estimate the solubility parameter and its components of diacetone alcohol, $CH_3COCH_2C(OH)(CH_3)_2$

*Solution*
The values of the group contributions are the following: (p. 218).

TABLE 7.10

Values of increments in Hoy's System (1985), for the molar attraction function

| Groups | $F_{t,i}$ $(J \cdot cm^3)^{1/2}/mol$ | $F_{p,i}$ $cm^3/mol$ | $V_i$ $cm^3/mol$ | $\Delta_{T,i}$ – | $\Delta_i^{(0)}$ – |
|---|---|---|---|---|---|
| —CH₃ | 303.5 | 0 | 21.55 | 0.023 | 0.022 |
| —CH₂— | 269.0 | 0 | 15.55 | 0.020 | 0.020 |
| >CH— | 176.0 | 0 | 9.56 | 0.012 | 0.013 |
| >C< | 65.5 | 0 | 3.56 | 0 | 0.040 |
| =CH₂ | 259 | 67 | 19.17 | 0.018 | 0.019 |
| =CH— | 249 | 59.5 | 13.18 | 0.018 | 0.0185 |
| =C< | 173 | 63 | 7.18 | 0 | 0.013 |
| CH_ar | 241 | 62.5 | 13.42 | 0.011 | 0.018 |
| C_ar | 201 | 16 | 7.42 | 0.011 | 0.015 |
| —HC=O | 600 | 532 | 23.3 | 0.048 | 0.045 |
| >C=O | 538 | 525 | 17.3 | 0.040 | 0.040 |
| —COOH | 565 | 415 | 26.1 | 0.039 | 0.039 |
| —COO— | 640 | 528 | 23.7 | 0.047 | 0.050 |
| —CO—O—CO— | 1160 | 1160 | 41.0 | 0.086 | 0.086 |
| ≡CN | 725 | 725 | 23.1 | 0.060 | 0.054 |
| —N=C=O | 736 | 8.2 | 25.9 | 0.054 | 0.054 |
| HCON< | 1020 | 725 | 35.8 | 0.062 | 0.055 |
| —CONH— | 1200 | 900 | 34.3 | 0.071 | 0.084 |
| —CONH₂ | 1131 | 895 | 28.3 | 0.054 | 0.073 |
| —OCONH— | 1265 | 890 | 34.8 | 0.078 | 0.094 |

| Groups | $F_{t,i}$ $(J \cdot cm^3)^{1/2}/mol$ | $F_{p,i}$ $cm^3/mol$ | $V_i$ $cm^3/mol$ | $\Delta_{T,i}$ – | $\Delta_i^{(0)}$ – |
|---|---|---|---|---|---|
| —OH→ (H-bonded) | 485 | 485 | 10.65 | 0.082 | 0.104 |
| —OH prim. | 675 | 675 | 12.45 | 0.082 | 0.049 |
| second. | 591 | 591 | 12.45 | 0.082 | 0.069 |
| tert. | (500) | (500) | 12.45 | 0.082 | 0.049 |
| —O— phenolic | 350 | 350 | 12.45 | 0.031 | 0.006 |
| ether | 235 | 216 | 6.45 | 0.021 | 0.018 |
| acetal | 236 | 235 | 6.45 | 0.018 | 0.018 |
| epoxide | 361 | 156 | 6.45 | 0.027 | 0.027 |
| —NH₂ | 464 | 464 | 17.0 | 0.031 | 0.035 |
| >NH | 368 | 368 | 11.0 | 0.031 | 0.0275 |
| >N— | 125 | 125 | 12.6 | 0.014 | 0.009 |
| —S— | 428 | 428 | 18.0 | 0.015 | 0.023 |
| —F | 84.5 | 73.5 | 11.2 | 0.017 | 0.006 |
| —Cl prim. | 419.5 | 307 | 19.5 | 0.017 | 0.031 |
| second. | 426 | 315 | 19.5 | 0.017 | 0.032 |
| arom. | 330 | 81.5 | 19.5 | 0.017 | 0.025 |
| >(Cl)₂ twinned | 705 | 572 | 39.0 | 0.034 | 0.052 |
| —Br aliph. | 528 | 123 | 25.3 | 0.010 | 0.039 |
| arom. | 422 | 100 | 25.3 | 0.010 | 0.031 |

| Configurations | $F_{(s)}$ | $F_{p,s}$ | $V_s$ | $\Delta_{T,s}*$ | $\Delta_{s,i}^{(p)}$ | Configurations | $F_{(s)}$ | $F_{p,s}$ | $V_s$ | $\Delta_{T,s}*$ | $\Delta_{s,i}^{(p)}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Base value (B) | 277 | — | — | — | — | Base value (B) | 47.5 | −19.8 | — | 0 | 0.0035 |
| Ring size (non-aromatic) | | | | | | Configuration isomerism | | | | | |
| 4-membered | 159 | 203 | — | 0 | 0.012 | cis | −14.6 | −14.6 | — | 0 | −0.001 |
| | | | | | | trans | −27.6 | −27.6 | — | 0 | −0.002 |
| 5-membered | 43 | 85 | — | 0 | 0.003 | Aromatic substitution | | | | | |
| 6-membered | −48 | 61 | — | 0 | −0.005 | ortho | 20.2 | −13.3 | — | 0 | 0.0015 |
| 7-membered | 92 | 0 | — | 0 | 0.007 | meta | 13.5 | −24.3 | — | 0 | 0.0010 |
| | | | | | | para | 83 | −34.0 | — | 0 | 0.006 |

For bi-, tri- and tetra-valent groups in saturated rings the Δ-values must be multiplied by a factor 2/3.

| Groups | $F_t$ | $F_p$ | $\Delta_T$ | V |
|---|---|---|---|---|
| 3—CH$_3$ | 910.5 | 0 | 0.069 | 64.65 |
| 1—CH$_2$— | 269.0 | 0 | 0.020 | 15.55 |
| 1 $>$C$<$ | 65.5 | 0 | 0 | 3.56 |
| 1 $>$CO | 538 | 525 | 0.040 | 17.3 |
| 1—OH tert. | (500) | (500) | 0.082 | 12.45 |
| Sum | 2283 | 1025 | 0.211 | 113.52 |

Furthermore we get:
B = base value = 277
$T_g/T_m = 0.576 + 0.211 - 0.045 = 0.742$
$\log \alpha = 3.39 \times 0.742 - 1.585 - 2.055 = 0.3019$, so $\alpha = 2.001$.
Finally we obtain for $\delta$ and the $\delta$-components:

$$\delta_t = \frac{2283 + 277}{113.52} = 22.55$$

$$\delta_p = 22.6 \left( \frac{1}{2.0} \cdot \frac{1025}{2560} \right)^{1/2} = 22.6 \times 0.45 = 10.1$$

$$\delta_h = 22.6 \left( \frac{1.0}{2.0} \right)^{1/2} = 22.6 \times 0.707 = 15.9$$

$$\delta_d = (22.55^2 - 10.1^2 - 15.9^2)^{1/2} = 12.3$$

The comparison with other values is as follows:

| | exp. | Small | Hansen | Hoftyzer -Van Krevelen | Hoy |
|---|---|---|---|---|---|
| $\delta_t$ | 18.8–20.8 | 23.0 | 20.7 | 21.9 | 22.6 |
| $\delta_d$ | – | – | 15.7 | 15.8 | 12.3 |
| $\delta_p$ | – | – | 8.2 | 7.4 | 10.1 |
| $\delta_h$ | – | – | 10.9 | 13.3 | 15.9 |

*Example 7.4*
   Estimate the value of $\delta$ and the $\delta$-components of polyvinyl acetate,

$$\begin{bmatrix} -CH_2CH- \\ \phantom{-CH_2}| \\ \phantom{-}O-CO-CH_3 \end{bmatrix}_p$$
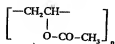
*Solution*
   From the tables 7.9 and 7.10 we obtain:

| Groups | $F_t$ | $F_p$ | $\Delta_t^{(T)}$ | V |
|---|---|---|---|---|
| —CH$_3$ | 303.5 | 0 | 0.022 | 21.55 |
| —CH$_2$— | 269.0 | 0 | 0.020 | 15.55 |
| —CH$<$ | 176.0 | 0 | 0.013 | 9.56 |
| —COO— | 640 | 528 | 0.050 | 23.7 |
| Sum | 1388.5 | 528 | 0.105 | 70.36 |

Base value = 277

$$\alpha = \frac{777 \times 0.105}{70.4} = 1.16; \quad \bar{n} = \frac{0.5}{0.105} = 4.76$$

So

$$\delta_t = \frac{1388.5}{70.4} + \frac{277/4.76}{70.4} = 19.72 + 0.83 = 20.55$$

$$\delta_p = 20.55 \left(\frac{1}{1.16} \cdot \frac{528}{1447}\right)^{1/2} = 20.55 \times 0.56 = 11.5$$

$$\delta_h = 20.55 \left(\frac{0.16}{1.16}\right)^{1/2} = 20.55 \times 0.37 = 7.6$$

$$\delta_d = (20.55^2 - 11.5^2 - 7.6^2)^{1/2} = 15.2$$

The comparison with other values is as follows:

|  | exp. | Small | Hansen | H.-Van K. | Hoy |
|---|---|---|---|---|---|
| $\delta_t$ | 19.1–22.6 | 19.2 | 23.1 | 19.4 | 20.55 |
| $\delta_d$ | – | – | 19.0 | 16.0 | 15.2 |
| $\delta_p$ | – | – | 10.2 | 6.8 | 11.5 |
| $\delta_h$ | – | – | 8.2 | 8.5 | 7.6 |

The results of the two algorithmic methods for estimation of the solubility parameter and its components (Hoftyzer-Van Krevelen and Hoy) are of the same order in accuracy (10%). So the safest way for estimation is to apply both methods, taking the average results.

To conclude we give the full equation which determines the solubility of a polymer in an organic liquid:

$$\boxed{\overline{\Delta\delta} = [(\delta_{d,P} - \delta_{d,S})^2 + (\delta_{p,P} - \delta_{p,S})^2 + (\delta_{h,P} - \delta_{h,S})^2]^{1/2}} \qquad (7.13)$$

For a good solubility $\overline{\Delta\delta}$ must be small ($\geqslant 5$).

*Influence of crystallinity*

It was pointed out from the beginning that the concept of the solubility parameter was applicable only to amorphous polymers.

In order to adapt the method to highly crystalline polymers some way must be found to deal with the heat of fusion ($\Delta H_m$) in the free enthalpy equation:

$$\Delta G_M = \{\Delta H_M + \Delta H_m\} - T\{\Delta S_M + \Delta S_m\}$$

Highly crystalline polymers such as polyethylene and poly(tetrafluoroethylene) are insoluble in all solvents at room temperature. These polymers, however, obey the solubility parameters rules at

$$T \geqslant 0.9 T_m .$$

For instance, polyethylene becomes soluble above 80°C. Furthermore, crystalline polymers do obey the rules even at room temperature in so far as swelling behaviour is concerned. This again is a demonstration that crystalline regions serve as apparent (physical) cross-links.

Some crystalline polymers with strong hydrogen bonding groups can be made to dissolve at room temperature. But in these cases a very specific interaction between polymer and solvent must occur. For example, cellulose is soluble in 70% sulphuric acid and in aqueous ammonium thiocyanate; nylon 6,6 is soluble in phenol and in a 15% calcium chloride solution in methanol.

*Other applications of solubility parameter diagrams*

Solubility parameter diagrams, e.g. $\delta_h - \delta_v$-diagrams, may be useful for the correlation of some phenomena attended with polymer–solvent interaction. These phenomena will only be *mentioned* here.

a. Characteristic parameters of dilute polymer solutions (see Chapter 9), e.g.:
    (1) the Mark–Houwink exponent $a$
    (2) the composition of solvent mixtures forming Θ-solutions with a given polymer
    (3) partial density of polymers in solution
b. Deterioration of polymers by solvents (see Chapter 21), e.g.:
    (1) swelling of polymers by solvents
    (2) solvent crazing and cracking
    (3) decrease of mechanical properties, e.g. tensile strength
c. Shrinkage of polymer fibres, immersed in solvents
d. Crystallization of polymers induced by solvents.

All these applications may lead to better and more consistent values of the parameter components.

*Solubility of (semi-) rigid polymers*

During the last decades the interest in semi-rigid aromatic polymers (aramids and arylates a.o.) is increasing. Dissolving of these polymers may be very difficult and requires rather unusual solvent. A survey of suitable solvents is given in table 7.11.

## C. INTERNAL PRESSURE

Spencer and Gilmore (1950) showed that the $p-v-T$ behaviour of polymer melts can be represented reasonably well by the following modified Van der Waals equation of state[1]:

$$(v - \omega)(p + \pi) = \frac{RT}{M_u} \qquad (7.14)$$

where $p$ is the applied pressure, $v$ is the specific volume of the polymer and $M_u$ the

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[1] A comparison between some empirical equations of state for polymers with regard to their standard deviations was made by Kamal and Levan (1973).

TABLE 7.11
Solvents for (Semi-) rigid-rod aromatic polymers (after Lenz (1985))

| Solvents | For (S-)R–R Aramids | For (S-)R–R Arylates |
|---|---|---|
| Very strong | Sulphuric acid (100%) | Trifluormethane sulphonic acid |
| Strong | Hydrofluoric acid<br>Chlorosulphonic acid<br>N,N-Dimethyl formamide + Li, Ca salts<br>N,N-Dimethyl acetamide + Li, Ca s.<br>Hexamethyl phosphoramide + Li, Ca s.<br>N-Methyl pyrrolidone + Li, Ca s.<br><br>N,N,N',N'-tetramethylurea<br>1.3.dimethyl-imidazolidinone<br>N,N,N',N'-tetramethyl malonamide | p-Chlorophenol<br>p-Chlorophenol/tetrachloroethane<br>p-Chlorophenol/o-dichlorobenzene<br>p-Chlorophenol/tetrachl.eth/phenol<br>Phenol/tetrachloroethane 60/40<br>Trifluoroacetic acid/methylene<br>chloride 60/40 or 30/70<br>Pentafluoro-phenol<br>p-Fluoro phenol<br>1.3.Dichlorol,1,3,3 tetrafluoro<br>acetone hydrate (=DCTFAH)<br>DCTFAH/perchloroethylene 50/50<br>DCTFAH/TFA/methylene chloride/<br>perchloroethylene 25/15/35/25 |
| Weak | N-methyl caprolactam<br>N-acetyl pyrrolidone<br>N,N-dimethyl propionamide<br>N-methyl piperidone | Trifluoroacetic acid (= TFA)<br>Tetrachloroethane<br>N,N-Dimethyl formamide |

molecular weight of an "interacting unit". $\pi$ and $\omega$ are constants which must be determined experimentally, just as the interaction unit $M_u$. $\pi$ in this equation is the *internal pressure*, which is independent of specific volume and, therefore, of temperature and pressure. It is obvious that the internal pressure will be related to the cohesive energy density (both have the dimension $J/cm^3 = N/cm^2$).

Spencer and Gilmore evaluated the constants $\pi$ and $M_u$ from a series of $p$–$v$ measurements at fixed temperatures. In synthetic linear polymers $M_u$ could be identified with the molecular weight of the structural unit. In this case ($M_u \omega = V(0)$) the equation of state becomes:

$$(V - V(0))(p + \pi) = RT \qquad (7.15)$$

At atmospheric conditions the internal pressure $\pi$ is much greater than the external pressure $p$, so that for the liquid polymer:

$$\pi = \frac{RT}{V(T) - V(0)} \approx \frac{R}{E_1} \qquad (7.16)$$

The same result is obtained by differentiation of the equation of state:

$$\left(\frac{\partial v}{\partial T}\right)_p = \frac{R}{M_u \pi}$$

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TABLE 7.12
Equation of state constants[1]

| Polymer | $\pi$ (bar) | | $\omega$ (cm$^3$/g) | |
|---|---|---|---|---|
| | exp. | calc. $\pi = R/E_1$ | exp. | calc. $\omega = V(0)/M$ $= 1.3 V_w/M$ |
| polyethylene | 3290 | 3470 | 0.88 | 0.95 |
| polypropylene | 2470 | 2700 | 0.83 | 0.95 |
| poly(1-butene) | 1850 | 2030 | 0.91 | 0.95 |
| poly(4-methylpentene) | 1050 | 1360 | 0.83 | 0.95 |
| polystyrene | 1870 | 1460 | 0.82 | 0.79 |
| poly(methyl methacrylate) | 2180 | 1730 | 0.73 | 0.73 |
| poly(caproamide) (nylon 6) | 1110 | 1180 | 0.62 | 0.815 |
| poly(hexamethylene sebacamide)(nylon 6,8) | 540 | 515 | 0.77 | 0.75 |
| polycarbonate | 460 | 610 | 0.56 | 0.695 |

[1] Experimental data from Spencer and Gilmore (1950) and Sagalaev et al. (1974).
Conversion factors: 1 bar = $10^5$ N/m$^2$ = 0.987 atm; 1 cm$^3$/g = $10^{-3}$ m$^3$/kg.

or

$$\pi = \frac{R}{M_u\left(\dfrac{\partial v}{\partial T}\right)_p} = \frac{R}{M_u e_1} = \frac{R}{E_1}$$

In table 7.12 the results calculated by means of eq. (7.16) are compared with the experimental data. The figures obtained are of the right order of magnitude.

Smith (1970) derived an equation of state for liquid polymers based on the hole theory of liquids. For higher temperatures, this equation can be reduced to a form equivalent to that of eq. (7.14).

It should be remarked that for cellulose derivatives (cellulose acetate, butyrate and ethylcellulose) the values of $M_u$ were found to be much smaller than the molecular weight of the structural units.

By means of eq. (7.15) a good impression of the $p$–$v$–$T$ behaviour of a polymer melt can be obtained if no data are available at all. Since $V(0) \approx 1.3\ V_w$ and $E_1 \approx 10.3 \times 10^{-4}$ $V_w$, $V_w$ only has to be calculated from group contributions in this case.

*Example 7.5.*
Estimate the specific volume of molten polypropylene
(a) at 200°C, 1 atm
(b) at 250°C, 1 atm
(c) at 200°C, 600 atm

*Solution*
We can calculate $v$ with the aid of a modification of eq. (7.14):

$$v = \omega + \frac{RT}{M_u(p + \pi)}$$

The following data may be used:

$R \quad = 83.14\, \text{cm}^3 \cdot \text{bar} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$

$M_u \quad = 42.1\, \text{g/mol} = M$

$\omega \quad = \dfrac{1.3\, V_w}{M} = \dfrac{1.3 \times 30.68}{42.1} = 0.947\, \text{cm}^3/\text{g}$

$V_w \quad = 30.68\, \text{cm}^3/\text{mol (table 4.11)}$

$E_1 \quad = 0.0307\, \text{cm}^3 \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$

$\pi \quad = \dfrac{R}{E_1} = \dfrac{83.14}{0.0307} = 2700\, \text{bar}$

Calculation leads to the following results:

| $T$ | $p$ | $v_{calc}$ | $v_{exp}$ |
|---|---|---|---|
| °C | bar | cm³/g | cm³/g |
| 200 | 1 | 1.30 | 1.34 |
| 250 | 1 | 1.33 | 1.39 |
| 200 | 600 | 1.23 | 1.28 |

The experimental data were determined by Foster et al. (1966).

From the equation of state, equations for the *thermal expansion coefficient* ($\alpha$) and for the *compressibility* ($\kappa$) can be obtained. Rearrangement of eq. (7.15) gives

$$V = V(0) + \frac{RT}{p + \pi} \tag{7.17}$$

from which the following partial derivatives are obtained:

$$\left( \frac{\partial V}{\partial T} \right)_p = \frac{R}{p + \pi} \quad \text{and} \quad \left( \frac{\partial V}{\partial p} \right)_T = -\frac{RT}{(p + \pi)^2} \tag{7.18}$$

Substitution gives:

$$\alpha = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_p = \frac{1}{T + \dfrac{V(0)}{R}\, (p + \pi)} \tag{7.19}$$

$$\kappa = -\frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_T = \frac{1}{(p + \pi) + \dfrac{V(0)}{RT}\, (p + \pi)^2} \tag{7.20}$$

The compressibility $\kappa$ is the reciprocal of the compression modulus or bulk modulus of the material. This important property will be discussed in Chapter 13 (mechanical properties of isotropic solid polymers).

The application of eq. (7.15) is restricted to polymer melts. For amorphous polymers

TABLE 7.13
Comparison of $\pi$ and $e_{coh}$ at 20°C

| Polymer | $\pi$ (bar) | $e_{coh}$ (bar) |
|---|---|---|
| polyethylene | 3200 | 2500/2900 |
| polyisobutylene | 3300 | 2500/2700 |
| polystyrene | 4600 | 3000/3600 |
| poly(chlorotrifluoroethylene) | 3700 | 2200/2600 |
| poly(vinyl acetate) | 4300 | 3600/5100 |
| poly(ethyl acrylate) | 4400 | 3500/3700 |
| poly(methyl methacrylate) | 3800 | 3400/6900 |
| poly(propylene oxide) | 3700 | 2300/4200 |
| poly(dimethyl siloxane) | 2400 | 2200/2400 |

Conversion factor: 1 bar $= 10^5$ N/m$^2 = 0.987$ atm.

below the melting point, the internal pressure $\pi$ may be defined as well:

$$\pi = \left(\frac{\partial U}{\partial V}\right)_T = T\left(\frac{\partial p}{\partial T}\right)_v - p \tag{7.21}$$

where $U$ is the internal energy per mole, but here $\pi$ is dependent on $T$ and $p$.

Values of the internal pressure for some polymers at room temperature have been mentioned by Allen et al. (1960). They appeared to be of the same order of magnitude as the cohesive energy density $e_{coh}$. A theoretical deviation by Voeks (1964) resulted in:

$$\pi \approx 1.3 \, e_{coh} \tag{7.22}$$

Values of $\pi$ and $e_{coh}$ for a number of polymers are compared in table 7.13, which shows eq. (7.22) to be valid as a first approximation.

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